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THESIS

ASSESSING THE OPERATIONAL EFFECTIVENESS OF A SMALL SURFACE COMBAT SHIP IN AN ANTI-SURFACE WARFARE ENVIRONMENT

by

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June 2013

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The design and capabilities of current naval ships may not meet the demands of naval operations such as anti-piracy, search and rescue, maritime interdiction, and force protection. Smaller vessels, especially Offshore Patrol Vessels, are better suited for these types of missions due to their affordability, speed, and flexibility. However, deciding on the requirements for a flexible, yet mission-effective, naval vessel requires the simultaneous consideration of technical inputs and operational needs.

The model-based ship design approach ensures that the mission requirements are linked to the capability analysis. In this way, Navy needs are better translated into ship requirements, and the decision makers get what they really need to acquire at the end of the process. The first step of this approach is assessing the operational effectiveness of the ships. This is done utilizing the combat modeling platform Map Aware Non-Uniform Automata (MANA)—and the power of Design of Experiments—to simulate how various potential capabilities, tactics, and rules of engagement affect mission outcomes.

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Anti-Air Warfare
AIS	Automatic Identification System
ASNET	Application System for Naval Evaluation and Testing
ASUW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
CART	Classification and Regression Tree
CO	Commanding Officer
COA	Course of Action
CONOPS	Concept of Operations
DTA	Defense Technology Agency
HVU	High Value Unit
INCOSE	International Council on Systems Engineering
LH	Latin Hypercube
MANA	Map Aware Non-Uniform Automata
MANA-V	Map Aware Non-Uniform Automata – Vector
MBSE	Model-Based Systems Engineering
MOE	Measure of Effectiveness
MOP	Measure of Performance
NATO	North Atlantic Treaty Organization
NICOP	Naval International Cooperative Opportunities in Science & Technology Program
NOB	Nearly Orthogonal, Nearly Balanced
NPS	Naval Postgraduate School
ONR	Office of Naval Research
OPV	Offshore Patrol Vessel
OR	Operations Research
OSN	Orizzonte Sistemi Navali
OTC	Officer in Tactical Command
PRONTO	Partnership for Research on Naval Technology and Operations

ROE	Rules of Engagement
SE	Systems Engineering
UAV	Unmanned Aerial Vehicle

EXECUTIVE SUMMARY

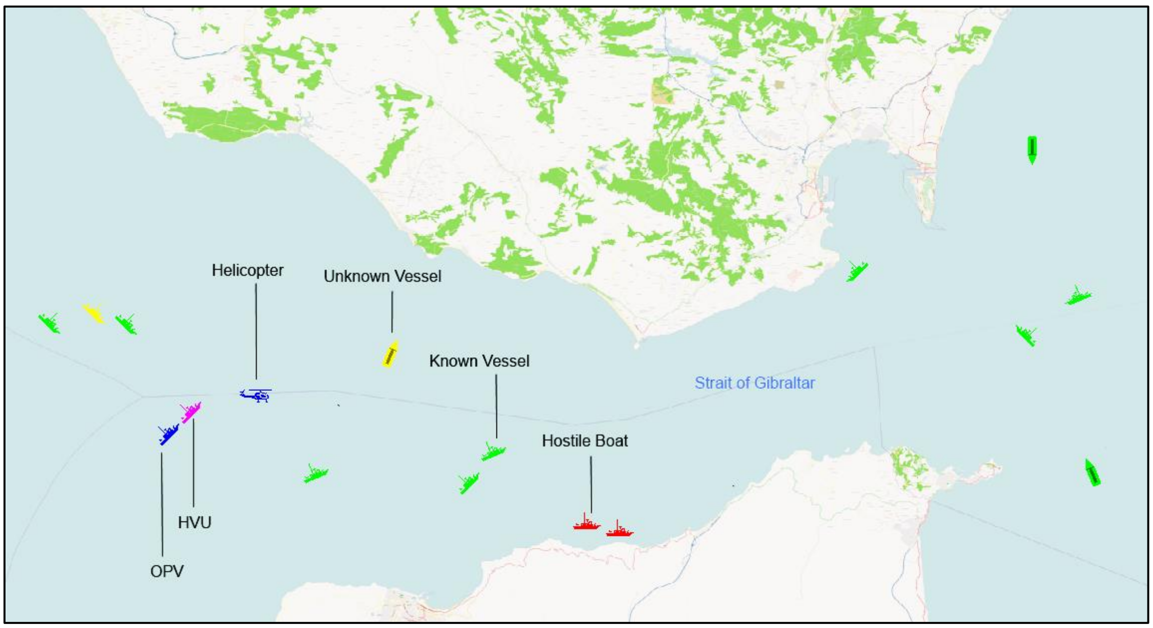
Surface combatants are one of the most valuable assets of a country. They provide security on the sea and protect a nation’s interests across the globe. For these reasons, surface combatants need to be not only capable, but also flexible and ready to fight any threat in this rapidly changing world.

Modern maritime menaces are threatening the shipping lanes and merchant vessels as well as the warships. Operations such as naval escort, anti-piracy, and maritime interdiction have begun to take the place of conventional naval warfare. However, existing ships were not specifically built for these modern tasks, and they are extremely expensive to risk in such missions. Moreover, they are not flexible enough to deal with small targets. Therefore, most navies have started building smaller, more flexible ships to cope with evolving maritime threats.

Assembling a modern, capable, and flexible fleet is challenging. The acquisition of new naval ships requires thorough analysis of the potential vessel’s capability, cost, and operational effectiveness. NPS is a participant in an Office of Naval Research (ONR) initiated project that focuses on the decisions involved in the early stages of the shipbuilding process. The NPS Operations Research and Systems Engineering departments are working together to form a decision-making tool, called the NPS Dashboard, that demonstrates the trade-space among capability, cost, and operational effectiveness of the naval ships. The purpose of this thesis is to help NPS integrate the operational effectiveness of an Offshore Patrol Vessel (OPV) within an anti-surface warfare (ASUW) environment using the NPS Dashboard.

Analyzing the operational effectiveness of a ship requires a scenario to build a combat model and a modeling platform to run multiple simulations. The scenario studied in this research is based on an incident that occurred 2002. In the scenario, the terrorists are planning to perform a suicide attack on a high

value unit (HVU) in the Strait of Gibraltar. The mission of the OPV is to escort the HVU while crossing the strait. If the HVU can pass through the strait, then it is assumed to be a mission success; otherwise, if it gets hit, the mission is assumed to be a failure. This scenario is instantiated in an agent-based combat modeling platform called Map Aware Non-Uniform Automata (MANA). MANA provides powerful tools for realistically representing the world in a simulation environment. A screenshot of the combat model used for this research is shown below.



There are six types of vessels in the scenario: HVU (pink), OPV (blue), helicopter (blue), hostile boats (red), known vessels (green), unknown vessels (yellow).

A Design of Experiments (DoE) approach is used for varying controllable and uncontrollable factors that are affecting the outcome of the mission. Controllable factors include the capability, tactics, and rules of engagement (ROE) that are related to the decisions about friendly assets. Uncontrollable factors are related to hostile boats, known vessels, and unknown vessels. The data analysis is done using regression tools and partition trees. The results of the analysis show that both capability choices and tactical decisions have substantial effects on the result of a naval mission. Several of the key drivers of mission success in this scenario are shown below.

Factors	Capability	Tactics	ROE
Main Gun Presence	x	x	x
Leading Ship Choice		x	
Range to Start Counter Measures	x	x	x
Auxiliary Gun Hit Probability	x	x	
Helicopter Presence	x	x	x
OPV Maximum Speed	x		

Key decision factors that affect mission success.

Most decisions about a naval ship's capabilities are made prior to the design of the ship. For better decisions, the decision maker needs to know the trade-offs between certain options. The analysis for the operational effectiveness of the ships is therefore crucial. The analyst helps the decision maker choose the best available ship design among the alternatives. Furthermore, the tactical decisions of the naval officers are also paramount for accomplishing a mission. This thesis shows how both the capability and operational decisions can be analyzed in the early stages of the ship design. Even the concept of operations (CONOPS) for various tasks can be planned along with the ship design process.

In the past, the experience of the sailors was the main driver of the tactical decisions. Today, it is the technology and the science that shape tactical decision making more intensely. Naval officers should know the characteristics of their ships, and they should rely not only their experience but also on analytical tools to form their decisions. Choosing the right course of action may reduce the emphasis on capability as the primary factor in decision making. This change has the potential to reduce the acquisition cost of a naval ship while improving the navy's prospects for achieving mission success.

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I. INTRODUCTION

"He who rules the seas, rules the world"

– Admiral Barbaros Hayrettin Pasha

A. OVERVIEW

In the past two decades, there has been a significant shift in naval missions toward operations other than war. Counter-piracy, search and rescue, maritime interdiction, maritime patrol, and naval escort operations are the main focus of most fleets today; however, the vessels that are currently being used in such operations were mainly built for other purposes. For instance, in August 2009, the North Atlantic Council approved "Operation Ocean Shield" to fight piracy in the Gulf of Aden. Among six surface ships that were assigned in the January-June 2012 rotation of this NATO mission, one was a destroyer and three were frigates ("NATO - Counter-piracy operations," n.d.). Although those warships can be used in such missions, how reasonable it is to risk a destroyer or a frigate to fight with terrorist boats or pirates?

Figure 1. NATO warships in SNMG2 operation (image from Allied Maritime Command Naples – NATO, http://www.manp.nato.int)

Many surface vessels that perform these modern tasks, as in the NATO Task Force example, are sophisticated warships capable of anti-surface warfare (ASUW), anti-air warfare (AAW), and anti-submarine warfare (ASW). Although these sophisticated multi-mission capable fleets are able to achieve good results in expeditionary warfare against a strong enemy (Murphy, 2007), the capabilities of those ships will probably be used in less than 1% of their total life time. It seems a sound reason to build capable ships in case of a conventional war, and one can claim that capable ships are built to be used in that small period of their life time; nevertheless, navies should optimize their efforts and resources in some way to find a better mix of vessel types and a better mix of systems that constitute the vessels.

While frigates and destroyers seem to be the best available options that can perform offshore operations, they are expensive to build and operate. On the other hand, smaller combatants are much cheaper and better suited for modern naval operations due to their flexibility. Therefore, many nations have begun reshaping their fleets to meet emerging operational demands: (1) they have started building smaller, yet sophisticated multi-mission capable combatants such as Offshore Patrol Vessels (OPVs) and Littoral Combat Ships (LCSs) that can be operated in a variety of maritime roles; (2) they have initiated the development of new tactics and counter measures to better deal with the new threats. The ship design and the acquisition processes, however, remains almost the same.

Despite technological advances in the last few decades, the ship design and the acquisition processes have not yet been able to keep pace with the rapid changes in use of technology (Ryan & Jons, 1992). Cost effectiveness and operational effectiveness are important, and it is extremely hard to achieve both using a traditional ship design process. Acceptable levels of effectiveness for both measures are more likely to be achieved with the use of technology and virtual environments. Moreover, utilizing the simulations and analytical models to build decision making tools will ensure collaboration between warfighters and engineers in the early stages of the process. Therefore, exploiting technology is paramount for accomplishing a navy's objectives and increasing the effectiveness for both cost and operations (Mizine, Wintersteen, & Wynn, 2012).

B. BACKGROUND

In December 2010, Orizzonte Sistemi Navali (OSN), an Italian contractor and whole warship design authority, and the Office of Naval Research (ONR), initiated a project called "the Application System for Naval Evaluation and Testing (ASNET), Partnership for Research on Naval Technology and Operations (PRONTO), Naval International Cooperative Opportunities in Science & Technology Program (NICOP)." The main purpose of this project is to analyze the operational effectiveness of ships using simulation and analytical models, to create a ship synthesis model, and most importantly, to develop decision making tools for ship designs using a model-based ship design approach. These tools will ensure that decision makers gain useful insight by exploring the trade space between factors affecting ship design and make informed decisions (Perra, Guagnano, & Bonvicini, 2012).

The model-based ship design approach used in this project is fundamentally different from the way surface combatants have been built in the past. Previously, the focus has been on engineering design criteria; mission types and operational environments have not been considered until after the ship design is essentially complete. Nevertheless, the model-based approach ensures that the mission requirements are linked to the capability analysis during the ship production process. Using this method, which is essentially the application of Model-Based Systems Engineering (MBSE) to decision making, helps ensure that the Navy's needs are better translated into ship requirements, and the decision makers get what they really need to get at the end of the process (Robinson, Tramoundanis, Harvey, Jones, & Wilson, 2010).

The chosen subject of the ASNET PRONTO NICOP project is OPVs; therefore, the scenarios, the cost data, and capability analyses are based on

OPV characteristics. The Naval Postgraduate School (NPS), Georgia Institute of Technology, University of Genoa, and some other institutions are participating in this effort. The role of NPS is important in the project. The Operations Research (OR) and Systems Engineering (SE) departments are collaborating to create a dashboard that displays cost, capability, and operational trade-offs (Figure 2). The operational experience of the students and the faculty members is leveraged especially in building scenarios and simulation models. The insights gained from this work are frequently shared with ONR, OSN, and other participants during the workshops and the meetings.

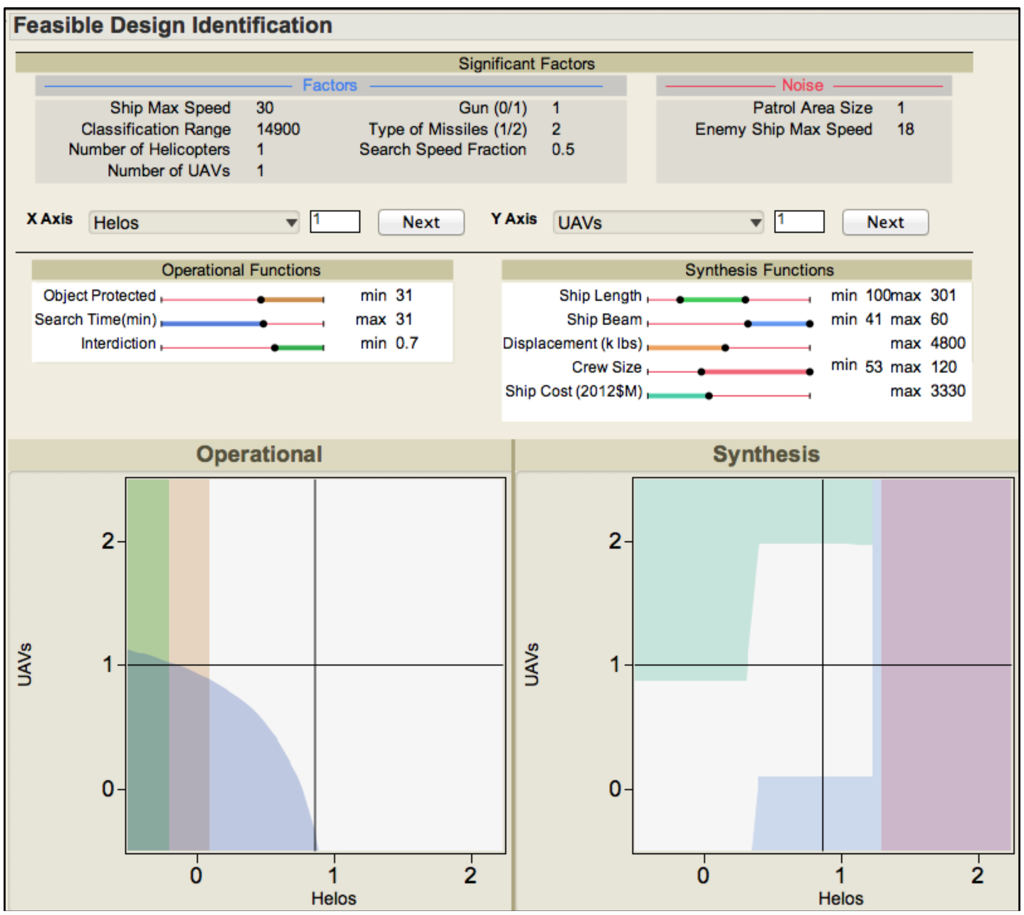

Figure 2. NPS Dashboard showing linkage of operational and physical trade-space.

As shown in Figure 3, three main categories of data are fed into forming the ship synthesis dashboard:

- Operational Effectiveness
- Capability
- Cost

The operational effectiveness data and the cost estimation data are mostly provided by the OR students, whereas the capability data are provided by students in the SE curriculum.

Figure 3. A sample list of Measures of Effectiveness (MOEs) and Measures of Performance (MOPs) to include in the dashboard.

Until now, several OR students built ASUW, Search and Rescue, and Maritime Interdiction Operation scenarios to evaluate key performance factors for ship designs. In their theses, their primary goal was to establish interchangeability with the models OSN created, which were simple and unrealistic. Moreover, those theses made limited comments on how tactics affect the results. Therefore, more realistic and advanced scenarios need to be created to be able to develop a truly useful dashboard. The factors that affect the ship design needs to be reconsidered as well.

C. RESEARCH QUESTIONS

This research detailed in this thesis focuses on the following questions related to the improvement of the ship design process:

- Based on a realistic and an advanced ASUW scenario, which ship design factors are key drivers of OPV performance in ASUW?
- What are the strengths and limitations of utilizing Map Aware Non-Uniform Automata – Vector (MANA-V), an agent-based modeling platform developed by New Zealand's Defense Technology Agency (DTA), to construct advanced and realistic scenarios for evaluating effectiveness of naval ships?
- How do different ship capabilities, tactics, and Rules of Engagement (ROE) affect the mission success?

D. SCOPE OF THE THESIS

A recent thesis by Jason McKeown analyzed the operational effectiveness of an OPV in an ASUW environment (McKeown, 2012). His model was based on a swarm attack scenario, and his main concern was to establish interchangeability with OSN model as mentioned above. In his scenario, the hostile boats were trying to reach a goal line, and they were not able to attack the OPV.

In light of the increase in maritime terrorism, it is also reasonable to expect an individual boat attack on a friendly ship while it is passing through a strait, refueling in a port, or patrolling the area. The main focus of this thesis is, therefore, assessing the mission effectiveness of a surface combat vessel in a realistic ASUW environment. An advanced asymmetric warfare scenario that was not previously implemented by OSN or NPS students is built and analyzed as part of this thesis. The factors tested are more realistic, and several tactics, such as changing the course of the ship after facing an attack, are analyzed to better understand how they change the response surface. Additionally, hostile boats are smart in this scenario. For instance, they are able to commit a kamikaze attack on the friendly ships.

E. CHAPTER OUTLINE

Chapter II is the literature review that touches on the tools used in this thesis, the naval warfare areas, the OPVs, and MBSE. Brief descriptions based on the published references prepare the reader for the following chapters.

Chapter III contains the development of the combat model and a thorough description of the operational scenario used in this thesis. The types of ships used in the combat model are explained in this chapter as well.

Chapter IV covers the exploration of the combat model. It starts with the description of the experimental design used for the simulations and continues with the explanations of the controllable and the uncontrollable factors. Following this discussion, the model output is analyzed using several types of data analysis approaches, including regression and partition tree analysis. Significant factors are discussed along with the operational insights. Other implementations of the scenario are explained as well.

Chapter V concludes the thesis. It gives a summary of the study and provides recommendations and suggestions for further research.

F. BENEFITS OF THIS STUDY

The results of this study are being used to augment the ship synthesis model built by the Systems Engineering department, and ultimately provide ASNET PRONTO NICOP project participants with a decision making tool for naval ship design. This study is also likely to help decision makers obtain a better understanding of the factors effecting ASUW for surface combatants. Since the factors examined by this thesis are related—but not limited—to OPVs, the insights obtained from this study can potentially be used for other ship types, including frigates, fast patrol boats, or coast guard boats. Additionally, this study demonstrates how tactics may affect mission success and how naval officers should use their firepower and maneuvering capability wisely.

II. LITERATURE REVIEW

A. ANTI-SURFACE WARFARE AND MARITIME TERRORISM

There are three primary categories of naval warfare: surface, air and submarine (Cole, 2007). Among those three warfare areas, surface warfare is perhaps the most dominant one, mainly because other areas of warfare usually take place in actual war conditions. The *Department of Defense Dictionary of Military and Associated Terms* describes surface warfare as "That portion of maritime warfare in which operations are conducted to destroy or neutralize enemy naval surface forces and merchant vessels" (*DoD Dictionary,* 2006). The term anti-surface warfare (ASUW) is generally used in a similar meaning, and can be defined as operations that are performed against surface vessels utilizing radar, guns, or any other means (Cole, 2007).

The reason why ASUW is the most common type of warfare lies behind this fact that ASUW operations not only include fighting with enemy state surface vessels, but also include fighting with asymmetric threats such as small suicide vessels or pirate boats. Naval vessels can face maritime threats at any time, since the terrorists and pirates can easily purchase and possess boats and attack a merchant vessel or a warship; therefore, those boats cause a threat, and they must be neutralized or destroyed whenever necessary.

Figure 4. A helicopter firing warning shots in front of the pirate boat (image from Allied Command Operations – Nato, http://www.aco.nato.int)

Even though the term “maritime terrorism” has been in the literature for more than a few decades, it was not really spelled out loudly until a series of incidents started in 2000. In January 2000, terrorists tried to attack USS The Sullivans (DDG-68) in Yemen. They failed because the terrorist boat sank right before the attack. Following this event, the terrorists attacked the USS Cole (DDG-67) with a suicide boat, killing 17 of the crew members, in October 2000. Almost two years after these incidents, in October 2002, a boat with explosives hit the French oil tanker Limburg which was close to Yemen coastal waters (Luft & Korin, 2004). These are just a few examples of how, with just a small boat, terrorists can cause damage to multi-million/billion dollar ships and—more importantly—kill tens of innocent people. There have also been many other terrorist activities which were prevented in their planning phases. In June 2002, for instance, Moroccan officials arrested a group of terrorists suspected of planning an attack on U.S. and British merchant vessels when passing through the Strait of Gibraltar (Maggio, 2008). These incidents show that maritime terrorism is a problem that must be prevented by any means, and the surface combatants must be ready to fight the terrorists at sea.

Figure 5. USS Cole after the attack in October 2000 (image from *New York Times*, http://www.nytimes.com)

B. AGENT-BASED MODELING AND MANA

In recent years, there has been an increase in the use of agent-based modeling and simulation. The agent-based modeling approach provides exceptional tools for modelers to represent the real world within a computer program. The agent-based models consist of autonomous entities called agents, and the set of rules which determine the interactions between agents and the environment surrounding them (Bonabeau, 2002). Although there is not a precise definition of an "agent" (Macal & North, 2009) or "agent-based simulation," in the agent-based modeling concept, the agents can be defined as the representation of the real world objects in an artificial environment (Cioppa, Lucas, & Sanchez, 2004). The agents can have behaviors, which makes the agent-based modeling technique unique. These autonomous entities are aware of the events that they can detect by organic/inorganic sensors, and they respond to the environment with actions defined by algorithms.

There are many tools that can be used for agent-based modeling. These include general purpose programs such as Microsoft Excel VBA, C++, JAVA; computation and statistics programs such as MATLAB, Mathematica, R; and dedicated agent-based modeling platforms such as NetLogo, Repast, AnyLogic, MANA (Macal & North, 2009). Each of these software packages has some superiority in various real word applications, i.e., business applications, biological applications, and medical applications; nonetheless, when it comes to military applications, not all of them are capable of modeling the non-linear and complex nature of the military conflicts (Lauren & Stephen, 2002).

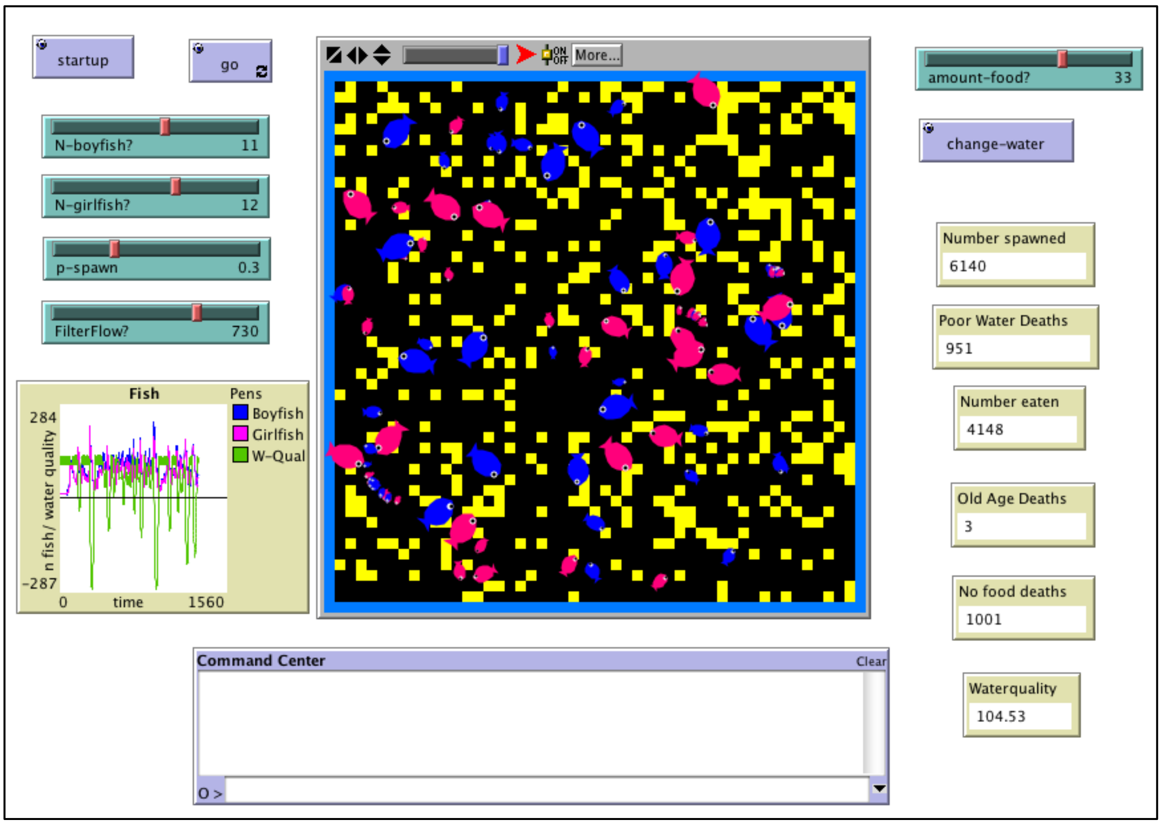

Figure 6. NetLogo is a widely used agent-based modeling platform (image from Science Education Resource Center, http://serc.carleton.edu)

Military conflicts usually exhibit complexity in the interaction between the agents with other agents and the environment. Additionally, agent positions in space change rapidly throughout time, and the population that the agents represent is usually heterogeneous (Bonabeau, 2002). All these attributes show that agent-based modeling is a proper tool to represent military operations, and choosing the right agent-based combat modeling platform will help military analysts to better represent the military tasks in a computer program. There are several agent-based modeling programs that can be practically used for modeling operational scenarios, including MANA, Pythagoras, and JANUS (Cioppa et al., 2004). Among these programs, MANA stands out as the most user friendly platform, and it is has been widely used by NPS faculty and students for almost 10 years. Military applications of agent-based modeling and simulation done using MANA include maritime protection of critical infrastructure assets (Lucas, Sanchez, Martinez, Sickinger, & Roginski, 2007), counter-piracy operations (Tsilis, 2011), UAV operations (Raffetto, 2004), and a comparison of warships against threats in confined waters (Ozdemir, 2009).

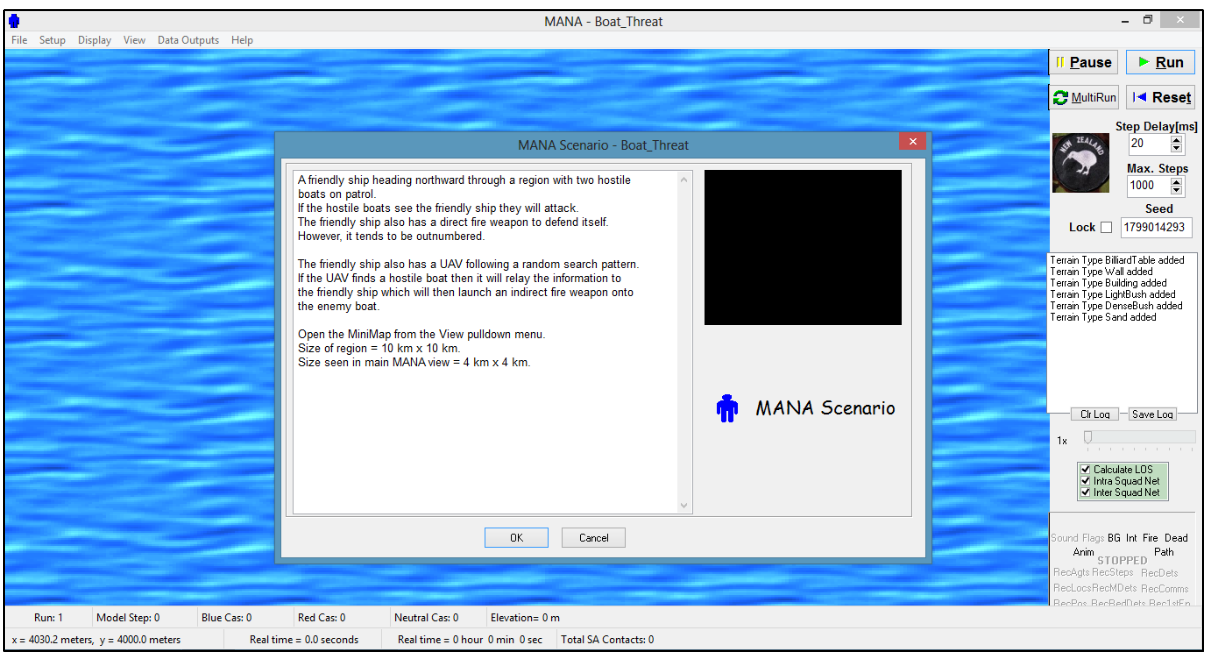

Figure 7. Screenshot of agent-based combat modeling platform MANA.

Designed by the Operational Analysis personnel of the New Zealand's DTA, MANA is an agent-based distillation model that has been available for more than ten years now (Lauren & Stephen, 2002). The key attributes of MANA which make it a useful tool for military applications are the situational awareness of the agents, advanced communication capabilities within squads and with other agents, the interaction of entities with friends and foes, and the user friendly design of the program.

There are four main sets of parameters that form agent behaviors in MANA (McIntosh, Galligan, Anderson, & Lauren, 2007):

- *Personality weightings* determine the willingness of agents to perform a particular action.
- *Movement constraints* modify the basic personality weightings of the agents.
- *Intrinsic capabilities* determine the physical characteristics of the agents such as sensors, weapons, or fuel level.
- *Movement characteristic adjustments* ensure that agent actions change in different terrain conditions and different situations.

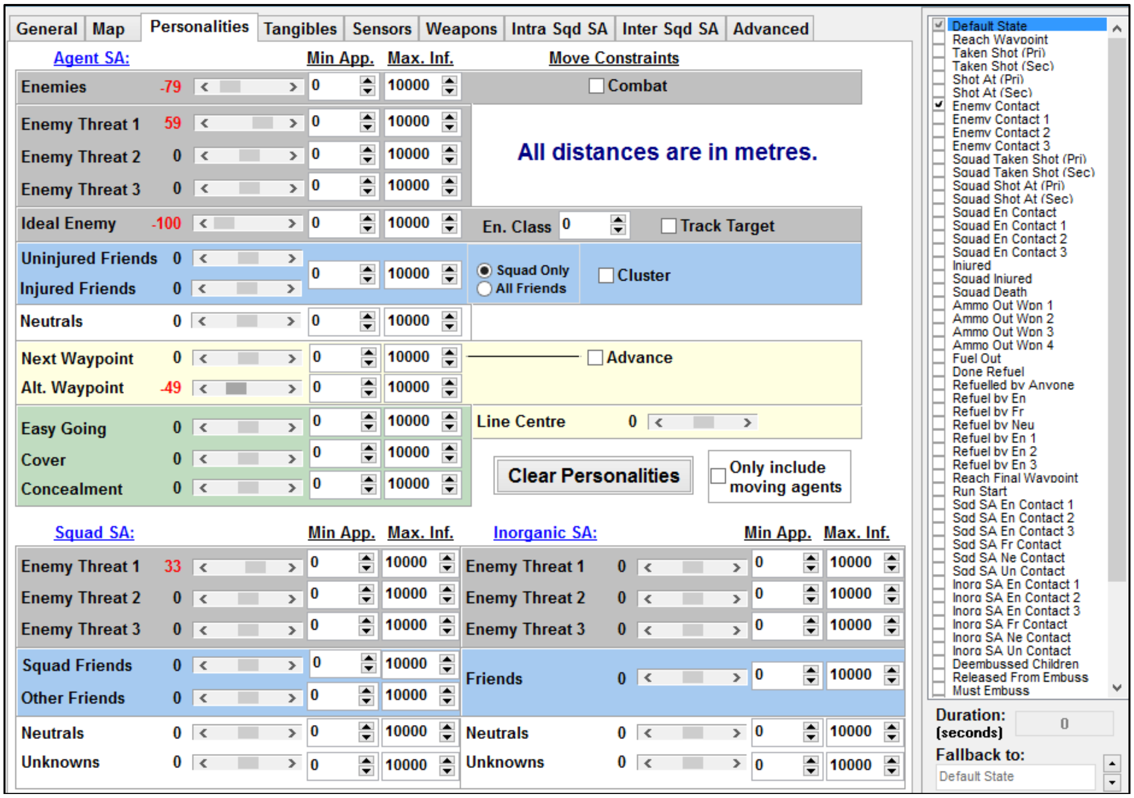

Figure 8. MANA-Screenshot of the "Squad Properties."

Just recently, DTA released the new version of MANA, namely MANA-V. "V" stands for both vector and five. In this version, the programmers replaced the cell-based movement of previous versions with vector-based movement, which allows building larger battlefield regions with panning and zooming options, and allows defining the distances and the attributes such as speed and range in real-world units, such as nautical miles (knots) or meters, rather than pixels (McIntosh, 2009). In this thesis, MANA-V version 5.01.04 is used for modeling and simulation.

C. DESIGN OF EXPERIMENTS

In the real world, experiments are usually built varying less than a handful of factors or variables. Utilizing the power of computers, on the other hand, it is possible to build simulations with more variables (Kleijnen, Sanchez, Lucas, & Cioppa, 2005). However, increasing the number of variables often causes high runtimes despite the modern computers. Even with the technological advances and supercomputers, it may take months to run a simulation experiment with a large number of factors using a brute force approach. Utilizing design of experiments (DOE), coupled with the powerful computers, solves this problem. DOE makes it possible to build simulations with a relatively high number of parameters, and it gives an acceptable screening property of the response surface, which leads to gaining better insights from the experiment.

The experimental design approach allows the analyst to provide more information to decision makers in a relatively small amount of time and helps them better understand the factors affecting the results (Kleijnen et al., 2005). Instead of changing factors one at a time or choosing design points with trial-error, DOE establishes smart ways of designing an experiment, which will yield important insights both to the analyst and the decision makers (Sanchez, 2007). In addition to exploring more factors, DOE also helps the analyst spend less time on the simulation runs and more time on the analysis.

There are several DOE techniques in the literature. The ones specifically useful in simulation design include factorial designs, fractional factorial designs, central composite designs, and Latin hypercube (LH) designs. Each of these techniques has some advantages and disadvantages depending on the number of factors, screening capabilities, and response surface complexity (Figure 9). For instance, with only a few factors, coarse grids might be useful. On the other hand, if the number of the factors is very large, LH designs are more efficient than the other designs, since they provide well screening of the response surface and yield similar information with significantly less computational effort (Sanchez, 2007).

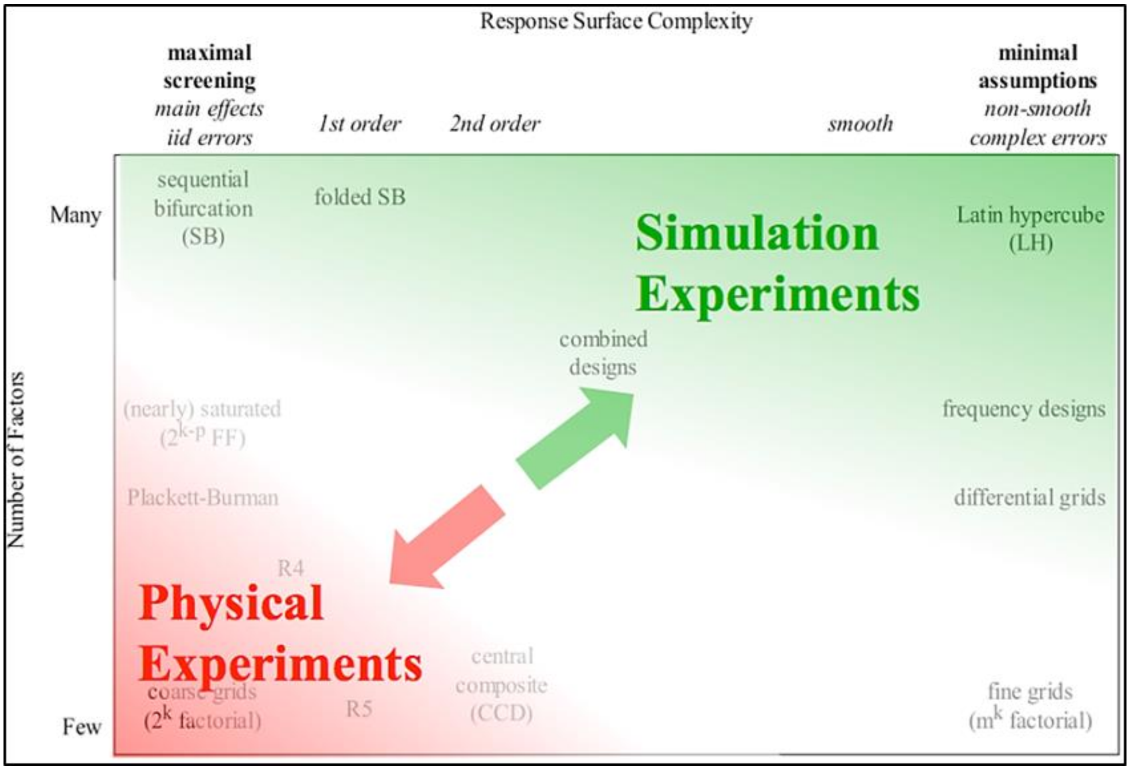

Figure 9. Recommended designs according to the number of factors and system complexity assumptions (Adapted from Kleijnen et al., 2005)

A nearly orthogonal, nearly balanced (NOB) mixed design approach is used to build the experiment in this thesis (Vieira, Sanchez, Kienitz, & Belderrain, 2011). The main advantage of this technique is that it accommodates not only continuous factors, but also discrete and categorical factors in the design.

D. OFFSHORE PATROL VESSEL (OPV)

Since the industrial revolution, surface combatants have evolved rapidly. Naval shipyards are now able to build multi-purpose warships such as cruisers, destroyers, and frigates, which are the most powerful naval assets of a country. These ships can operate anywhere globally with less dependence on coastal facilities or resources. However, they are not the only fighting ships that a navy has. There is a variety of fighting ships, ranging from small patrol boats to cruisers, each of which has advantages in different situations. For instance, small patrol boats have a small draft, which allows them to navigate through shallow waters close to the shore. On the other hand, larger ships are able to perform multiple tasks simultaneously. They can deal with aircraft, surface ships, missiles, and submarines at the same time, and they can perform counter-measures against a variety of enemy forces.

OPVs are relatively small combatants when compared to frigates and destroyers. They are more like corvettes, with less fighting capability. Their main purpose is maintaining maritime security inshore and offshore, and they can be deployed globally (Kimber & Booth, 2010). Many countries do not really need sophisticated naval combatants, and some countries cannot afford capable ships (Annati, 2009). Being cheaper yet flexible, OPVs are great options for those countries throughout the world.

Nations build OPVs mainly to use in peacetime operations, and the primary functions of the OPVs are ASUW and AAW; however, they can also be used in ASW and other warfare areas, if built with such capability (Eames, 1985). Escort operations, anti-piracy operations, and humanitarian efforts are some of areas where OPVs are used.

E. MODEL-BASED SYSTEMS ENGINEERING (MBSE)

Technological advances led humans to build complex systems over the years. While the systems are becoming more and more complex, it is becoming extremely hard for engineers and decision makers to deal with development of these diverse systems. Surface combatants are examples of such complex systems. They consist of various subsystems such as weapons and sensors. Moreover, the stakeholders or shareholders that work on the ship building process come from a wide range of industries (Calvano, Jons, & Keane, 2000). These make the shipbuilding process extremely complicated, especially if the warship is the first one of its class.

Systems engineering tries to find a way to deal with the complex systems. According to Kossiakoff et al. (2011), the function of systems engineering is "guiding the engineering of the complex systems." Furthermore, it is argued that the systems engineering effort is centered on the systems as whole, not on the separate parts (Kossiakoff, Sweet, Seymour, & Biemer, 2011).

Model-based systems engineering (MBSE) is a new approach to systems engineering, and it is seen as the future of the systems engineering by International Council on Systems Engineering (INCOSE). Systems Engineering Vision 2020 describes MBSE as “the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” (Crisp, 2007). This approach is mainly useful for highly complex systems such as warships and maintains the link between the engineers and the decision makers (Robinson et al., 2010).

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III. MODEL DEVELOPMENT

A. BACKGROUND

Operations to fight terrorist boats or pirate ships have become a crucial aspect of naval operations since terrorists have started being a threat to military and civilian ships in the maritime domain. In the last 15 years, there has been a significant increase in the number of incidents in which terrorists attacked a warship or a merchant vessel and killed tens of sailors. Additionally, there were some incidents in which the terrorists were not able to carry out their outrageous plans. For instance, in June 2002 a group of terrorists, who were planning an attack on two merchant vessels in the Strait of Gibraltar, were caught by Moroccan officials (Maggio, 2008).

Figure 10. There are various types of ships passing the Strait of Gibraltar at any moment of a day (from http://www.marinetraffic.com)

The fact that the officials arrested those terrorists does not mean that similar plans will not be put into practice by other groups. If a terrorist group fills a boat with explosives and approaches a ship in Strait of Gibraltar, it will be really difficult to identify that boat as a terrorist boat since there is large number of vessels in the strait at any moment (Figure 10). Therefore, naval escort ships need to be ready to protect both themselves and the merchant vessels against asymmetric threats. Most current naval vessels, however, are not particularly built to fight terrorist boats, and they are expensive to risk in such missions. As a consequence, many countries started building smaller yet flexible surface combatants, such as OPVs, to meet the demands of their navies. Nevertheless, finding the best mix of capabilities such as weapons and maximum speed is a problem that needs to be considered in the very beginning of the shipbuilding process (Mizine et al., 2012). A proper way to overcome this problem is building combat models and testing the operational effectiveness of the surface combatants in scenario-based simulation environments.

B. SCENARIO DESCRIPTION

In this thesis, the agent-based modeling platform MANA is used to model a naval escort mission scenario in an anti-surface warfare environment. The scenario is based on the Morocco incident that occurred in 2002. There are six types of agents in the scenario: the high value unit (HVU) being escorted, the OPV, the OPV's helicopter, terrorist boats, known vessels, and unknown vessels. A screenshot from MANA appears in Figure 11; note that the sizes of the agents are not to scale, but are magnified for easier visualization by the user. The allegiance of the HVU, OPV, and the helicopter is "friend," the allegiance of the terrorist boat is "hostile," and the allegiance of the known and unknown vessels is "neutral."

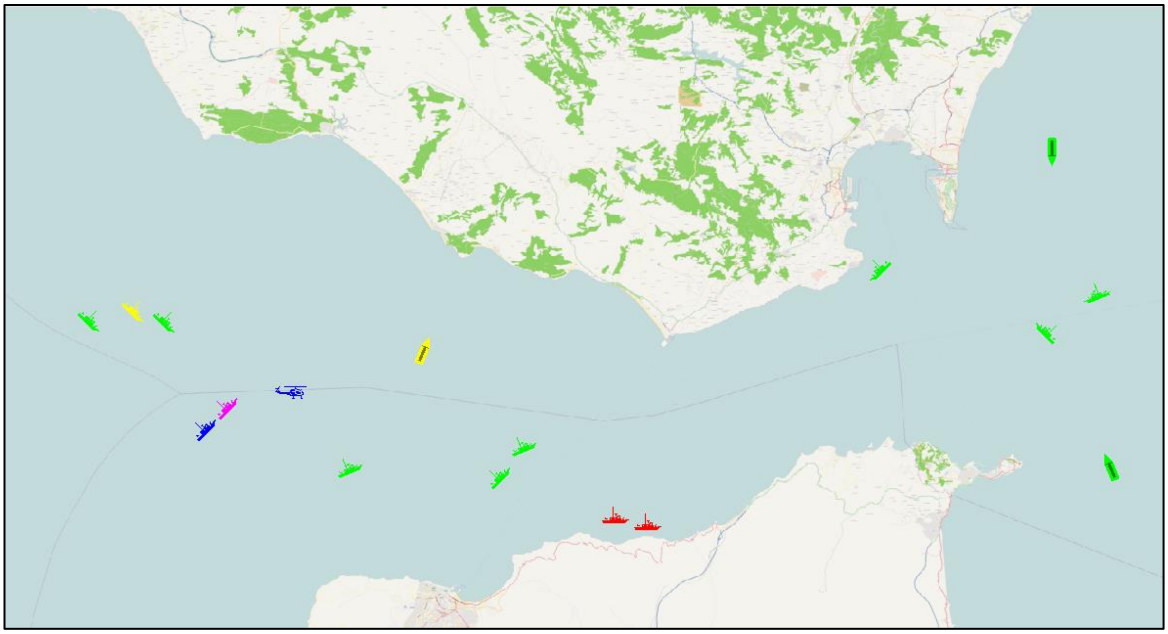

Figure 11. Screenshot of MANA. There are six types of agents in the ASUW scenario: HVU (pink), OPV (blue), helicopter (blue), terrorist boats (red), known vessels (green), unknown vessels (yellow).

1. Friendly Assets

The mission of the friendly assets is to cross the Strait of Gibraltar without allowing any damage to be caused to the HVU by hostile vessels. The OPV is tasked to protect the HVU from attacks that can occur in the passage. It has several guns, ranging from high caliber guns to machine guns. It also has a helicopter landing platform. The main role of the helicopter is to detect and classify unknown vessels. Its high speed and maneuverability give the friendly forces an advantage against the hostiles. The helicopter can also have a machine gun so that it can start firing before the hostile vessels come closer to the HVU.

2. Hostile Boats

The terrorist boats are loaded with explosives, and their purpose is to get closer to a high value unit (HVU) so that they can perform a suicide attack. The only target of the hostile boats is the HVU. They do not attack the OPV, but in some cases they may try to evade it. One of the critical properties of the terrorist boats is that they are initially acquired as unknown vessels in the friendly force radar/systems until they are classified as enemy. Therefore, either the helicopter classifies them as enemy, or the unknown vessels get closer to the OPV or HVU, and the friendly ships classify them depending on the range.

3. Neutral Ships

The known ships and the unknown ships are both neutral, and they do not pose a threat to friendly assets. The only difference between the two is that while the OPV can instantly classify the known neutral ships with the Automatic Identification System (AIS) device, unknown ships cannot be classified when they are initially detected. This occurs for several reasons, such as they are too small to carry an AIS device or their device is not working. Once the unknown vessels are classified, they become known vessels, and their color changes to green in MANA. The importance of the known and unknown vessels is to represent the real marine traffic of the Strait of Gibraltar as accurately as possible. When the neutral ships are close to the hostile boats, the OPV and the aircraft are unable to fire to the boats. Moreover, friendly assets need to put in an additional effort for classifying the unknown ships as neutral. This makes the situation more complicated and gives the terrorists a chance to approach at a closer distance without any classification by the friendly force.

C. SCENARIO ASSUMPTIONS AND LIMITATIONS

The scenario is based on a real incident; nevertheless, it is impossible to create a model that imitates the real world exactly. Therefore some assumptions need to be made, and the limitations of the modeling platforms need to be considered in order to build a model that can present useful insights.

1. Assumptions

The key assumptions used to build the model are the following:

- The OPV has an AIS receiver, which helps to detect and classify the neutral ships within some distance. Once they are classified, they become neutral ships.
- Most of the merchant vessels have AIS emitters. They provide their data to the friendly forces. However, some ships do not have AIS devices even though they are neutral. Those ships need to be detected and classified visually or by using radar.
- The terrorist boats can communicate with each other.
- The helicopter can classify the unknowns as hostile or neutral once it approaches within a certain distance to the target.
- The terrorists can only perform a kamikaze attack. They do not have a long range weapon such as a rocket.
- The probability of a hit for the weapons is constant within the minimum and maximum effective ranges, and zero outside the range.

2. Limitations

Most of the limitations are related to the combat modeling platforms. For instance, it is difficult to implement a naval formation using different squads; formation is only allowed for agents within squads. Another limitation is that it is difficult to implement tactics in the model. Nevertheless there are ways to overcome many such limitations. The personalities of the agents in MANA provide exceptional tools for implementing tactics and behaviors (Figure 12). Changing the levels for various parameters gives the modeler an opportunity to make the agents react to their environment in a smart way.

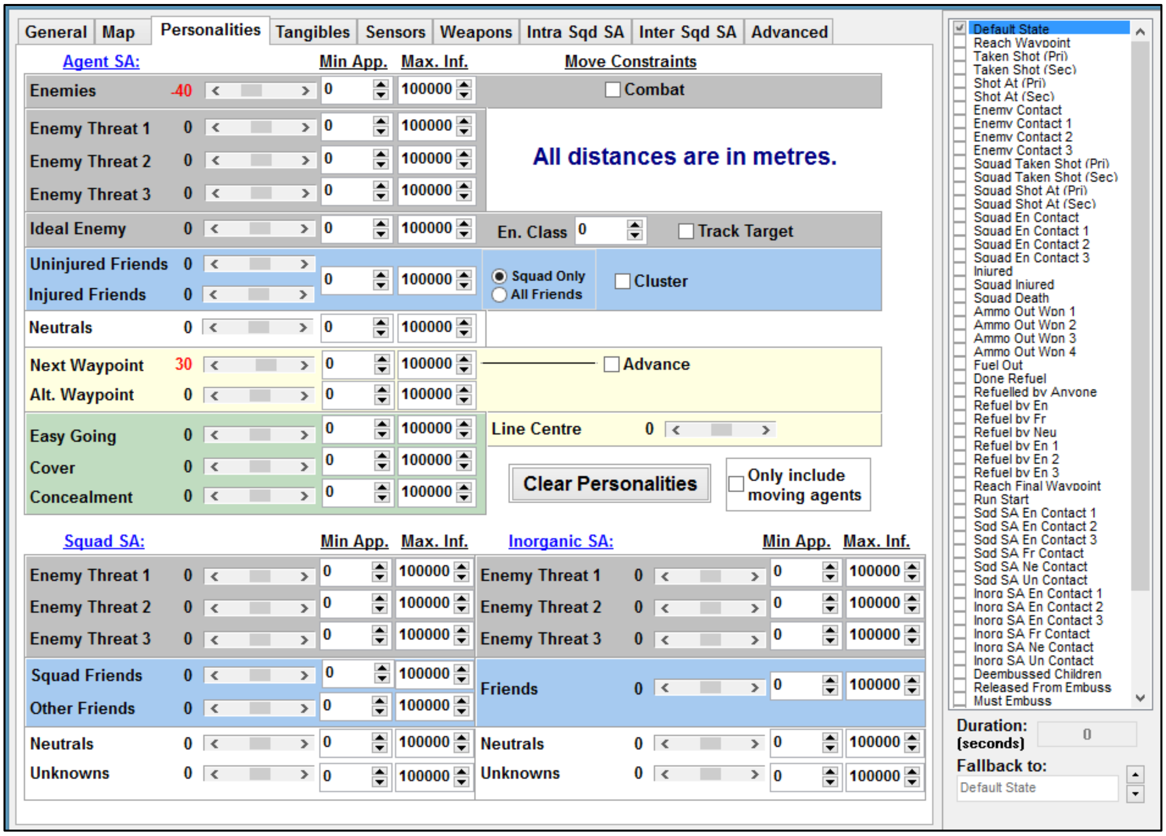

Figure 12. Personalities of the agents in MANA.

There are also limitations regarding classified information. For example, the probability of hit for a certain weapon is classified information, and it is not provided in any open source. Moreover, even if it were provided, there would still be some uncertainties about the probability of hit depending on the size of the target, weather conditions, etc. To overcome these types of limitations, properties of the agents having uncertainties are built as a factor in the DoE. By doing that, a wide range of levels for each property is tested. Moreover, this will allow the analyst with access to the classified information to pull out the setting of interest and come up with a proper result.

D. MEASURE OF EFFECTIVENESS

The only measure of effectiveness in the scenario is the probability of mission success. If the HVU can cross the Strait of Gibraltar and reach the goal line, it is a mission success. If at least one of the terrorist boats is able to attack the HVU, then it is a mission failure.

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IV. MODEL EXPLORATION

A. DESIGN OF EXPERIMENTS

Hundreds of factors affect the outcome of a military mission in the real world. These factors can be divided into two groups. The first group consists of controllable factors that can be manipulated or decided upon in advance or during the mission. The second group consists of uncontrollable or noise factors that cannot be controlled by any means. For instance, while choosing the speed to cross the strait is a controllable factor, the number of enemy forces is an uncontrollable factor.

In total, 35 factors are varied in the simulations, and they are discussed in the following section. Among these 35 factors, 29 are controllable factors and 6 are uncontrollable factors. The NOB Mixed Design spreadsheet is used to generate the experimental design in this analysis (Figure 13). This spreadsheet allows studying up to 300 factors with 512 design points (Vieira Jr., Sanchez, Kienitz, & Belderrain, 2012).

lo	0	0	0	0	0	0	0	-40	0
hi	1	1	1	1	1	1	25	0	1
decimals	0	0	0	0	0	0	0	0	0
discrete levs	2	2	2	2	2	2	2	2	2
factor name	Squad3_Acti	Squad2_Wea	Squad3_Wea	Squad2_Wea	Squad2_Wea	Squad2_Wea	Squad2_Age	Squad1_Age	Squad3_Acti
	1	1	1	0	1	0	25	0	1
	0	1	0	0	0	0	25	0	0
	0	1	0	0	0	1	0	0	0
	0	0	1	0	1	1	25	0	1
	1	0	0	0	1	1	0	-40	1
	1	0	0	1	1	1	0	-40	1
	1	1	0	1	0	0	25	0	0
	1	1	1	1	0	1	0	0	0
	0	0	1	1	0	0	25	0	1
	1	0	1	1	0	0	0	0	1
	1	1	0	1	1	1	25	-40	1
	0	1	1	0	1	0	0	0	1
	1	0	1	1	1	0	25	0	0
	1	1	1	1	0	1	25	0	1
	1	1	1	1	1	0	25	0	1
	0	1	1	1	1	1	25	0	1
	0	0	1	0	1	1	25	0	1

Figure 13. Partial Screenshot of Nearly Orthogonal Nearly Balanced Mixed Design spreadsheet.

The NOB Mixed Design spreadsheet ensures that the design has good space-filling properties and that the factors are nearly orthogonal. Orthogonality has some advantages when fitting a meta-model, because when the factors are uncorrelated, both the computation and the interpretation of the response surface simplifies (Kleijnen et al., 2005). The maximum correlation between the factors studied in this thesis is less than 0.03 which is considered to be very low. A scatter plot of a portion of the factors and the mean response is shown in Figure 14. The space-filling property can be seen with this graph.

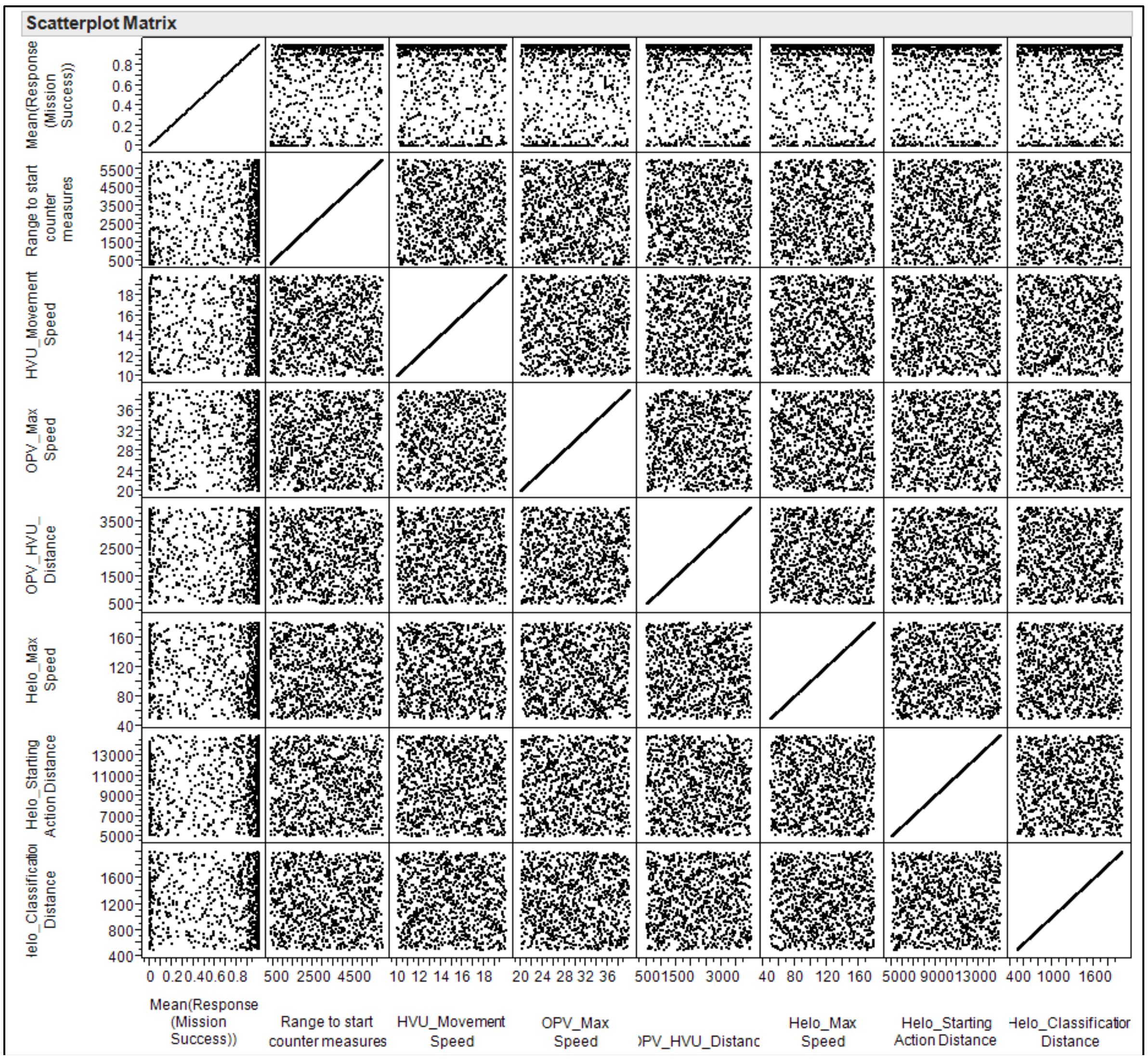


Figure 14. Scatter plot of part of the variables. Space-filling property of the NOB design can be seen with this plot.

B. CONTROLLABLE FACTORS

Controllable factors in the ASUW model consist of the tactics, ROE, and physical capabilities of HVU, OPV, and the helicopter. There are three ways for the decision maker or naval officer to control these factors:

- Selecting the capabilities of the systems that form the naval combatant prior to the shipbuilding process (e.g., maximum speed, presence of the helicopter platform). Factors of this type cannot be changed once the ship is commissioned.
- Changing the properties of the ship following its commissioning (e.g., number of machine guns, radar type/range). Factors of this type can be changed after the commissioning; however, it is not likely since changing these factors needs a significant amount of effort, money, and man-hours.
- Deciding how to use the current capabilities of the ship in a naval operation in the most efficient way (e.g., tactics, ROE).

The ASNET PRONTO NICOP project primarily focuses on the first option, which is selecting the capabilities of the surface combatants in advance while taking into consideration the operational effectiveness and cost effectiveness. On the other hand, the author believes that the tactical/operational decisions or ROE may have a paramount effect on the outcome of a mission, and the concept of operations can be analyzed along with the capability analysis. Therefore, the implications of various tactical/operational decisions and courses of action (COA) should be considered in the operational effectiveness studies. For example, the maximum speed of a surface combatant is a capability related issue. However, even if the speed of the ship is not very fast, the naval officer in charge may be able to exploit the enemy’s vulnerabilities to achieve a certain goal with effective use of tactics. For this reason, not only capability related factors, but also tactical and ROE related factors, are studied in this thesis.

1. HVU Factors

There are no factors that are directly linked to the capabilities of the HVU; nevertheless, some factors, such as speed to cross the strait, indirectly affect the HVU performance in the mission. These factors are explained in "Tactics and Rules of Engagement," later in this chapter.

2. OPV Factors

a. OPV Speed

In many scenarios previously implemented in MANA, once the speed of an agent was set, the agent could only move in that specified speed throughout the simulation runs. In this scenario, on the other hand, the OPV's speed is defined in two ways.

- When there is no enemy, the OPV moves at the speed with which the HVU passes through the Strait of Gibraltar. Depending on the design point, this speed can be as low as 10 knots and as high as 20 knots. The speed to cross the strait is related to tactics, ROE, and regulations at sea. It is explained in "Tactics and Rules of Engagement," later in this chapter.
- When a friendly asset classifies a boat as hostile, the OPV moves towards the hostile boat at its maximum speed, which ranges from 20 knots to 40 knots.

b. OPV Weapons

The OPV can have three types of weapons in the scenario: a large/medium caliber main gun, a small caliber auxiliary gun, and a machine gun. Each gun type has a different set of values for the following parameters: hit probability, maximum effective range, minimum effective range, and bursts of fire per minute.

The hit probability for a certain weapon is classified information and cannot be obtained from an open source. Moreover, the standard deviation of a gun's probability of hit is relatively high when compared to a missile's probability of hit. The reason for high variation is that the guns are less automated, and there are more factors affecting the gun fire. For instance, it is very difficult to hit a small speedboat, but it is relatively easy to hit a tanker. Therefore, there cannot be a fixed hit probability that fits every situation. For all these reasons, the hit probability is varied in the analysis.

Although it is fairly easy to set most of the weapon properties in MANA, it is not straightforward to set the inter-firing time. MANA uses the following equation for calculating the shots per second:

$$\frac{x}{100} = ShotsPerSecond$$

In his equation, x is the user input value. For instance, if the user sets x to 100, then the agent can fire one shot per second. Unfortunately, MANA does not provide a differentiation between a single shot and a burst of fire. While a single shot makes more sense for missiles, it does not make much sense when the weapon is a gun. Since the weapons used in this scenario are guns, a burst of fire is used instead of a single shot in the analysis. The factor used in place of "shots per second" is "bursts per minute." Therefore, the equation below is used to calculate the bursts per minute:

$$\frac{60 \cdot x}{100} = BurstsPerMinute$$

A burst depends on several factors such as aiming time, distance, reloading, target acquisition, and user preference (Abel, 2009). Thus, instead of using a fixed value, a range of values is tested in the experiment to see the effect of the inter-firing time to the response surface.

(1) Main Gun (Weapon 1). A warship's main gun can be a large caliber gun or a medium caliber gun. Many navies prefer medium caliber guns for their OPVs; therefore, the ranges for the main gun's general

characteristics were chosen based on a medium caliber 76 mm naval gun (Table 1).

Factor	Min	Max	Units
Hit Probability	0.1	0.9	-
Maximum Effective Range	7000	10000	meters
Minimum Effective Range	1000	2000	meters
Bursts per Minute	1	10	bursts

Table 1. OPV main gun factors and ranges.

The main gun's maximum effective range is substantially higher than the auxiliary gun's and machine gun's maximum effective ranges. Firing from a long range is particularly important in conventional warfare, but not necessarily when fighting with terrorists. In areas like the Strait of Gibraltar, there are so many merchant vessels that it is almost impossible to classify a ship within long distances. In this scenario, the only way to classify an unknown vessel from a long distance is with a helicopter. Therefore, even though the maximum effective range of the main gun ranges from 7000 meters to 10000 meters, the OPV cannot use its main gun if the enemy boat is not classified as hostile.

To see the effect of the main gun to the response surface, a factor that enables or disables the main gun is also added to the experimental design. This may help the decision maker to better understand the diverse effects of not using a main gun in such missions.

(2) Auxiliary Gun (Weapon 2). The auxiliary gun for the OPV is a small caliber gun. The ranges for the parameters of the auxiliary gun are chosen based on a 30 mm naval gun (Table 2). The auxiliary gun's presence is important especially when the OPV is not able use its main gun for some reason. If the hit probability of the auxiliary gun is high, it can be a game changer for friendly side.

Factor	Min	Max	Units
Hit Probability	0.1	0.9	-
Maximum Effective Range	1000	3000	meters
Minimum Effective Range	200	400	meters
Bursts per Minute	1	10	bursts

Table 2. OPV auxiliary gun factors and ranges.

(3) Machine Guns (Weapons 3, 4, 5). A machine gun is operated by OPV personnel, and it has a relatively short effective range when compared to the effective ranges of the main and the auxiliary guns. Its main purpose is to warn other ships and to protect its own ship from small targets.

The machine guns are very useful in crowded areas, such as straits, since it is extremely hard to classify a small boat from a long distance. It is also impossible to use missiles or long range guns at shorter distances. Additionally, it might be the case that a country's ROE may not allow their naval vessels to start firing at another vessel unless it approaches within a certain distance, such as 500 meters. In this case, the naval vessel can use its machine guns both for warning the approaching vessel and for protecting itself.

A 12.7 mm machine gun is used as a base for the ranges of the OPV's machine guns (Table 3). The minimum effective range for the machine guns is fixed at zero.

Factor	Min	Max	Units
Hit Probability	0.1	0.9	-
Maximum Effective Range	100	150	meters
Bursts per Minute	1	10	bursts

Table 3. OPV machine gun factors and ranges.

Another set of factors related to the machine guns is the number of machine guns used. In the scenario, the OPV can have at most three machine guns. Three factors are dedicated to enabling or disabling each machine gun in the experimental design. The guns are all interchangeable, so an alternative design would be use a single factor to set the total number of guns. Our approach can be easily extended for future work, if differences in gunner capabilities or positioning are explored.

3. Helicopter Factors

a. Helicopter Presence

Whether or not a helicopter is tasked in the escort mission is a factor in the experimental design. Although this factor can be related to the tactics, it may also be related to the design of the ship. If the ship has a helicopter platform, then it can perform helicopter tasks. If not, then the friendly assets will need a land-based helicopter tasked to support their mission.

b. Helicopter Speed and Sensors

The high speed capability of the helicopter makes it one of the most valuable assets of a warship. It can perform search, detection, and reconnaissance operations in relatively short amounts of time, with high accuracy. Technological advances also allow the helicopters to use cameras that help them better classify the targets. The factors of helicopters that are related to the speed and the sensors are shown in Table 4.

Factor	**Min**	**Max**	**Units**
Max Speed	50	180	knots
Detection Max Range	5000	15000	meters
Classification Max Range	500	2000	meters

Table 4. Helicopter’s maximum speed and sensor factors and ranges.

Helicopter speed is also defined in two ways.

- When there is no unknown vessel, the helicopter moves at the speed with which the HVU passes through the Strait of Gibraltar.

- When the helicopter detects an unknown vessel, it moves towards that target for classification at its maximum speed, which ranges from 50 knots to 180 knots.

The friendly assets have AIS devices, which allow them to classify almost all of the vessels in the strait. However, there are still some vessels that cannot be classified via AIS. Once those ships are detected, then the helicopter approaches them for classification. In the real world, the classification distance may depend on weather conditions, capability of the camera, or the training of the operators. Therefore, the classification range is designed to be factor in the experiment. This factor ranges from 500 meters to 2000 meters.

c. Helicopter’s Weapon

A 12.7 mm machine gun is used as a base for the ranges of the helicopter’s machine gun (Table 5). The minimum effective range for the machine guns is fixed at zero.

Factor	**Min**	**Max**	**Units**
Hit Probability	0.1	0.9	-
Maximum Effective Range	100	150	meters
Bursts per Minute	1	10	bursts

Table 5. Helicopter machine gun factors and ranges.

Whether the helicopter has a weapon or not is also a factor. In almost half of the simulation runs, the helicopter has a machine gun that is operated by helicopter crew. In the other half, it does not have any weapons. In this case, the helicopter’s only purpose is to detect enemy targets and send this information to the OPV and HVU.

4. Tactics and Rules of Engagement

From a military point of view, tactics can be defined as the art of using the capabilities of the naval forces in a battle, whereas ROE are directives issued by governments that allow or limit naval assets to use their forces (*DoD Dictionary,* 2006). Factors related to tactics and ROE are shown in Table 6.

Factor	**Min**	**Max**	**Units**
Speed to Cross the Strait	10	20	knots
Range to Start Counter Measures	300	6000	meters
Distance Between HVU and OPV	500	4000	meters
Distance Between HVU and Helicopter	3000	10000	meters
Leading Ship Choice	OPV	HVU	-
HVU's Response to Attack	Evade	Not Evade	-

Table 6. Factors of tactics and ROE.

These factors are mostly dependent on the decisions of the officer in tactical command (OTC). There is no right choice of parameters that can be used in every task; nevertheless, the results of this analysis may yield important insights about the tactical decisions in naval escort missions and some areas of ASUW. These factors are also important to demonstrate the fact that choice of different tactics or different COAs may result in different set of warship characteristics.

a. Speed to Transit the Strait

In most of the straits and canals all over the world, the coastal states adopt laws and regulations to prevent the collision of ships. They usually put a maximum and a minimum speed limit within the strait or canal. However, depending on the number of ships and the situation, the ships are allowed to use higher speeds.

In the Strait of Gibraltar, the recommended maximum speed limit is 13 knots (Arceredillo, Sagarminaga, de Stephanis, Cañadas, & Lago, 2008). Nevertheless the average speed is higher than 13 knots. If there is intelligence regarding a terrorist boat attack in the strait, with which speed should the OTC order the convoy to cross the strait? The factor "speed to cross the strait" is ranged from 10 knots to 20 knots to answer this question and to understand whether the speed has an effect on the mission success.

b. Range to Start Counter Measures

Countries have ROE that allow their warships to start firing on other ships when certain conditions are met. The factor "range to start counter measures" represents the distance at which the OPV is able to start firing if the hostile boat is within the maximum effective range of its weapons. This assumes the target ship is classified as hostile and all the necessary warnings are given. The range to start counter measures ranges from 300 meters to 6000 meters.

c. Distance between HVU and OPV

The distance between the HVU and the OPV is a tactical decision and is usually made by the OTC. For instance, when the direction of the enemy is unknown, it may be a good idea to keep the distance between the HVU and OPV small. On the other hand, if the enemy is expected from a certain direction, it may be a better idea to use the OPV in that direction with a greater distance between HVU and OPV. However, the direction from which the hostile boats approach is not known in this scenario, and this is usually the case in actual missions. To understand how the distance between the escort ship and the HVU affects mission success, a factor is added to the experimental design. This factor ranges from 500 meters to 4000 meters.

d. Distance between HVU and Helicopter

The distance between the HVU and the helicopter is also a tactical decision; however, it may not be as important as the distance between HVU and OPV due to the helicopter's high speed capability. This factor ranges from 3000 meters to 10000 meters.

e. Leading Ship Choice

The decision regarding the formation of the ships is a tactical decision as well. This decision is particularly important when the convoy does not have a helicopter. This factor has two options. The first is keeping the OPV in the forward position and making it the leading ship. The second is making the HVU the leading ship.

f. HVU's Response to Attack

The HVU has two options when the friendly assets classify a ship as hostile. It can either continue on the convoy's waypoint without changing its route, or it can change its route to evade the terrorist boat.

C. UNCONTROLLABLE FACTORS (NOISE FACTORS)

1. Hostile Boat Factors

There are three factors regarding hostile boats: the number of boats, the maximum speed of the boats, and whether or not they employ tactics to evade the OPV.

a. Number of Hostile Boats

The number of terrorist boats is a factor that ranges from one boat to ten boats. The location of the boats is selected randomly, and the terrorists are assumed to be capable of communicating with each other. Depending on the location of each individual boat, the terrorist boats are modeled to perform a swarm attack on the HVU.

b. Hostile Boat Speed

The speed of the terrorist boats ranges from 20 knots to 40 knots. The speed is very important for the terrorist boats when the speed of the OPV is lower than their speed, and when the number of bursts per minute for the OPV's weapon is not high.

c. Evade OPV

The terrorists can employ different tactics as well. The scenario was modeled such that the terrorist boats do not directly attack the OPV. Their only target is the HVU; however, they are aware of the OPV. Therefore, it may be a wise choice if they evade the warship, while at the same time approaching the HVU. Whether the terrorist boats evade or not is a two-level factor that represents the enemy tactics.

2. Known/Unknown Vessel Factors

The only factor regarding the known and unknown neutral vessels is their number. The initial location of the vessels has a high degree of randomness; however, this is not designed to be factor. The ranges of the neutral ships' factors are shown in Table 7.

Factor	**Min**	**Max**
Number of Known Vessels	10	30
Number of Unknown Vessels	1	10

Table 7. Factors of known/unknown vessels.

D. DATA ANALYSIS

1. Simulation Runs

The combat model for the operational ASUW scenario was built using MANA version 5.01.04. The author started the analysis with 100 replications for each of the 512 design points of the DoE. In the meantime, New Zealand's DTA fixed several errors in MANA, which were mostly GUI related errors, and in released version 5.01.05. This version was not tested by any NPS faculty or students before, and it did not prove to be operating well. Therefore, both for testing the new version of MANA and testing the baseline model, another 100 replications were run using the new version. This time, a different set of columns for factors was used in the NOB Mixed Design spreadsheet to increase the space-filling property of the design. Both sets of runs were analyzed, and the results showed that the two versions did not differ for this particular scenario. Thus, the two concatenated sets of runs, which sum up to 102400 runs with 1024 design points, are used throughout the data analysis.

In the initial design, the time step of the model was also a factor. The choice of time step is important because it directly affects the total time required to make the simulation runs, but overly large time steps can lead to unusual behavior and model artifacts (Buss & Al Rowaei, 2010). The values one, two, and five were tested in the simulation runs. The results of the runs with time step values one and two did not seem to be different, while the results of the runs in which the time step is five proved to be slightly different. This indicates that time steps of five or larger should be avoided, but there does not appear to be a need to reduce the time step even further. For this reason, and for the fact that it took less than 24 hours in a cluster to run 100 replications of this scenario, we decided to fix the time step to one.

2. Regression Analysis

There are several approaches to regression analysis. While some techniques yield similar results, others may result in different meta-models. Two techniques are used in this analysis: logistic regression and least squares regression. Additionally, partition trees are used to compare the significant factors with the significant factors of logistic regression and least squares regression meta-models.

a. Logistic Regression

The only MOE in this analysis is mission success. Therefore, the result of each scenario run is either a success or a failure. This produces a binary result, and fitting a logistic regression is a proper way to deal with binary response. The distribution of the response in the raw data is shown in Figure 15. Among 102400 replications, friendly assets achieved mission success in 74066 of the runs. The probability of the success in overall replications is around 0.72.

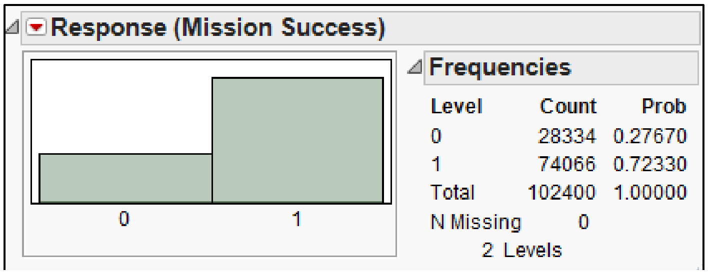


Figure 15. Distribution of the response.

The summary of the logistic regression model with all the main effects is shown in Figure 16. The p-value of this model is less than 0.0001, which proves that the saturated logistic regression model is significant when compared to the null model.

Whole Model Test

Model	-LogLikelihood	DF	ChiSquare	Prob>ChiSq
Difference	23004.326	35	46008.65	<.0001*
Full	37392.092			
Reduced	60396.418			

Figure 16. Summary of the logistic regression model.

The leading 15 factors of the logistic regression model sorted in the order of significance from high to low are shown in Figure 17. The first five factors in the list seem to have a huge impact on the response surface, whereas the other factors have much less impact. Moreover, whether or not the OPV main gun is enabled appears to be the most significant factor of all.

Parameter Estimates

Term	Estimate	Std Error	ChiSquare	Prob>ChiSq
OPV_Weapon1_Enable[0]	1.01602893	0.0102704	9786.7	<.0001*
RED_No.of.Agents	0.33265595	0.003571	8677.6	<.0001*
OPV_Forward Position[0]	0.87987545	0.010339	7242.4	<.0001*
Range to start counter measures	-0.0004297	5.8753e-6	5349.3	<.0001*
OPV_Weapon2_Probability	-2.6949762	0.0380387	5019.5	<.0001*
Helo_Active[0]	0.55865071	0.0096813	3329.8	<.0001*
RED_Movement Speed	0.06888563	0.0016536	1735.3	<.0001*
OPV_Weapon1_Probability	-1.4829545	0.0360533	1691.9	<.0001*
HVU_Evade[0]	0.37153035	0.0094871	1533.6	<.0001*
OPV_Weapon2_ShotperSecond	-0.0650704	0.0019035	1168.6	<.0001*
OPV_Max Speed	-0.046021	0.0016267	800.42	<.0001*
OPV_Weapon1_ShotperSecond	-0.0434965	0.0018913	528.94	<.0001*
OPV_HVU_Distance	0.00018018	9.2733e-6	377.52	<.0001*
RED_Evoid OPV (with levels)	0.01189559	0.0006433	341.98	<.0001*
OPV_Weapon4_Enable[0]	0.17035682	0.0092978	335.70	<.0001*

Figure 17. Parameter estimates for the logistic regression.

The purpose of this analysis is not predicting the mission success of an OPV in an ASUW mission, but rather understanding the factors affecting the mission success. Nevertheless, it is still possible to assess how well the meta-model predicts the mission success. The Receiver Operator Characteristic (ROC) curve is one way to evaluate the meta-models. As a rule of thumb, when the area under the ROC curve is between 0.8 and 0.9, the meta-model is considered to be predicting well; when it is higher than 0.9, the meta-model is considered to be predicting excellently (Hemmingsson, Uddén, & Neovius, 2009). The ROC curve of the logistic regression model is demonstrated in Figure 18. The area under the curve is 0.89, which proves that the meta-model is predicting fairly well.

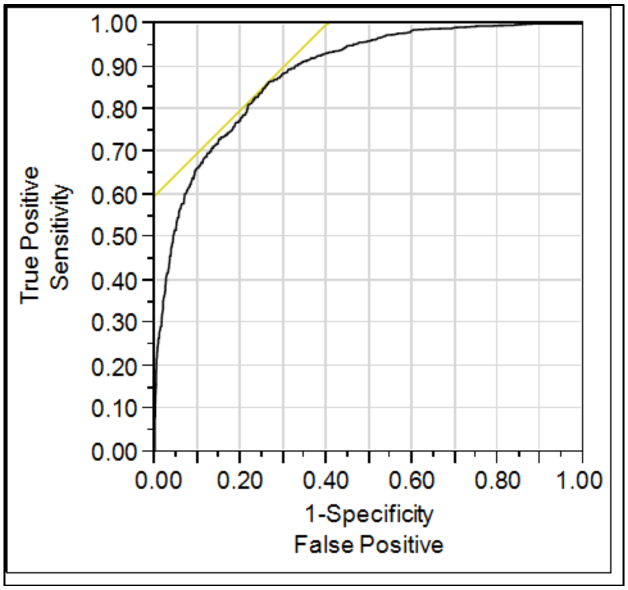


Figure 18. The ROC curve for logistic regression model evaluation.

b. Least Squares Regression

For any specific design point, even though all the values of the input parameters are the same, each simulation run (called a replication) produces different results due to the randomness embedded in the modeling platform. A designed experiment gives the analyst an opportunity to investigate a range of outcomes based on different parameter settings, but it is sometimes better to simplify the data to gain more insights. For instance, when dealing with a binary response, it is possible to take the mean of the response for all the replications at each design point. Then the aggregated average response values can be used to predict mission success. Taking the mean of the response for all replications of each design point yields a multi-level response ranging from zero to one. In this way, the analyst can fit a regular regression model to the aggregated data, and this might provide a better insight into the problem at hand because it is easy to interpret.

The distribution of the mean of the response in the aggregated data is shown in Figure 19. The overall proportion of mission success is 0.7233, which is equal to the proportion of mission success in the raw data. It is also worth noting that there is a large number of instances where the proportion of mission success is greater than 0.95 or lower than 0.05. This means it will be more difficult for a polynomial model to do an effective job of fitting the aggregated response data. Even so, it is interesting to see what factors are most important.

Stepwise regression methods and expert judgment are used to select the significant factors to fit the least squares regression model. The threshold for the p-values, or the significance level, which is used as evidence of statistical significance for terms included in the models (Htoon & Chan, 2010), is set to be very low to avoid over-fitting. This low p-value threshold also reduces the chances of "false positives" (Type I errors) when identifying important factors and allows us to have interpretable results. It is also true that for large data sets, such as those resulting from large-scale simulation experiments, regression models can contain terms that are statistically significant but not practically important. A low p-value threshold is useful for obtaining relatively parsimonious models in these situations.

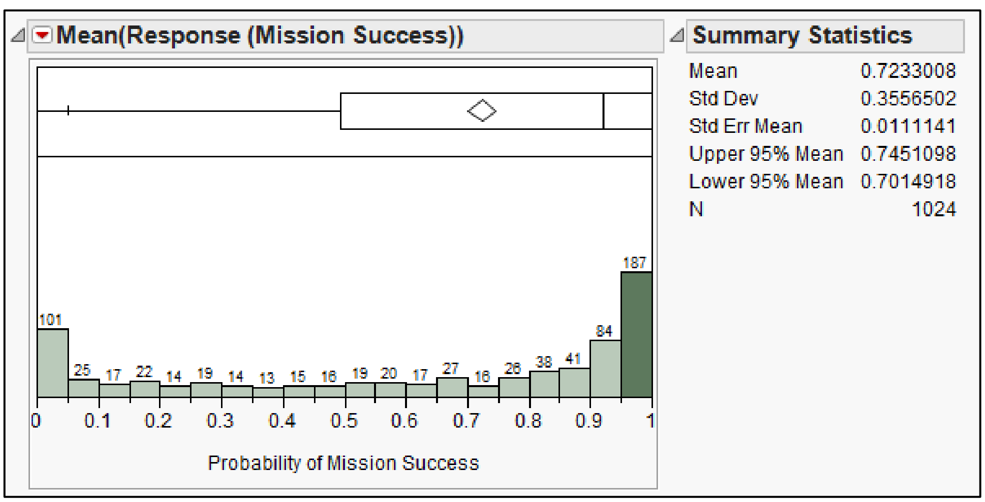


Figure 19. Distribution of the mean response. The total number of occurrences (N) is 1024. Among those occurrences, 187 of them resulted in with probability of mission success greater than 0.95.

(1) Main Effects Model. The Actual by Predicted plot and the Summary of the stepwise model, fitted with only the main factors without any interactions, are shown in Figure 20. Only 15 factors, which proved to be significant, are included in the model. The R-Square value is around 0.56. This value represents how much variability can be explained using this model. There is considerable randomness, as is often the case in the combat models, but the regression terms can help the analyst focus on what really affects the mission success.

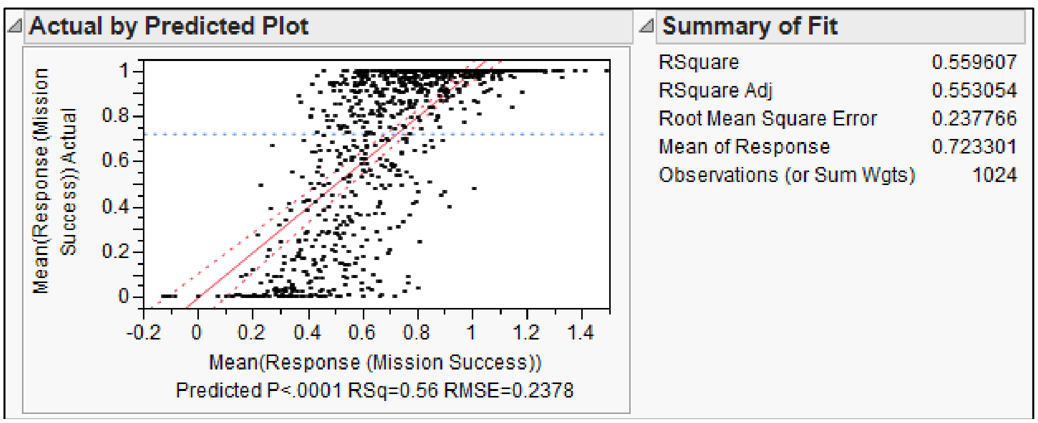


Figure 20. Actual by predicted plot and the summary of the fit for the main effects regression model.

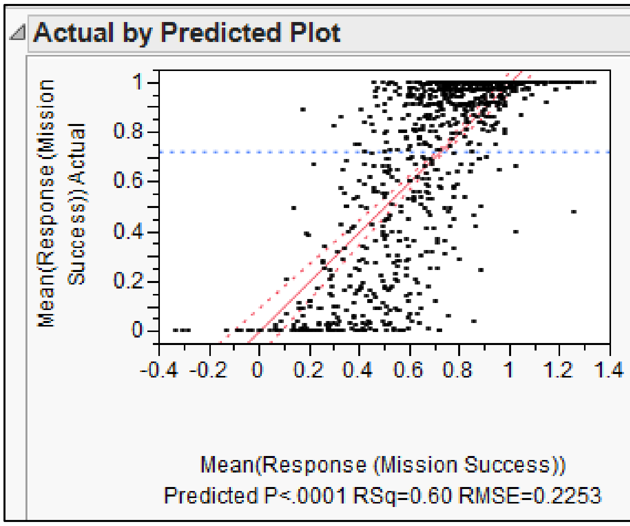
The sorted parameter estimates of the main effects model are shown in Figure 21. Note that the first five factors have a more significant effect on the probability of mission success when compared to others, as can be seen by the magnitudes of the t ratios. These five factors are exactly the same factors that showed up in the logistic regression model, as expected.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
OPV_Weapon1_Enable[0]	-0.128137	0.007437	-17.23	<.0001*
RED_No.of.Agents	-0.040321	0.002563	-15.73	<.0001*
OPV_Forward Position[0]	-0.102261	0.00745	-13.73	<.0001*
Range to start counter measures	5.503e-5	4.508e-6	12.21	<.0001*
OPV_Weapon2_Probability	0.3509198	0.028854	12.16	<.0001*
Helo_Active[0]	-0.062972	0.007443	-8.46	<.0001*
RED_Movement Speed	-0.00801	0.001285	-6.23	<.0001*
OPV_Weapon1_Probability	0.176017	0.028291	6.22	<.0001*
HVU_Evade[0]	-0.042083	0.007434	-5.66	<.0001*
OPV_Weapon2_ShotperSecond	0.0084448	0.001507	5.60	<.0001*
OPV_Max Speed	0.0047018	0.001285	3.66	0.0003*
OPV_Weapon4_Enable[0]	-0.022876	0.007443	-3.07	0.0022*
RED_Evoid OPV (with levels)	-0.001535	0.000514	-2.99	0.0029*
OPV_HVU_Distance	-2.09e-5	7.345e-6	-2.85	0.0045*
OPV_Weapon1_ShotperSecond	0.0042385	0.001491	2.84	0.0046*

Figure 21. Sorted parameter estimates of the main effects regression model.

(2) Second Order Model. The Actual by Predicted plot and the Summary of Fit built with the main effects, two-way interactions, and polynomials are shown in Figure 22. The R-Squared value of the second order model is higher than that of the main effects model, even though the second order model contains one less term and involves fewer factors. One might think that is why the R-squared value is not very high.



Summary of Fit

RSquare	0.604107
RSquare Adj	0.598614
Root Mean Square Error	0.225322
Mean of Response	0.723301
Observations (or Sum Wgts)	1024

Figure 22. Sorted parameter estimates for the stepwise regression model to include the main effects, two-way interactions, and polynomials.

The sorted parameter estimates are shown in Figure 23. The six most significant factors are the same as the factors of the main effects model, with a slightly different order.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
OPV_Weapon1_Enable[0]	-0.122462	0.00707	-17.32	<.0001*
RED_No.of.Agents	-0.038986	0.002432	-16.03	<.0001*
OPV_Forward Position[0]	-0.102047	0.007061	-14.45	<.0001*
OPV_Weapon2_Probability	0.3629253	0.027438	13.23	<.0001*
Range to start counter measures	5.4167e-5	4.289e-6	12.63	<.0001*
Helo_Active[0]	-0.063289	0.007052	-8.97	<.0001*
(Range to start counter measures-3150)*(Range to start counter measures-3150)	-2.251e-8	2.919e-9	-7.71	<.0001*
HVU_Evade[0]	-0.044864	0.007055	-6.36	<.0001*
RED_Movement Speed	-0.007591	0.00122	-6.22	<.0001*
OPV_Weapon1_Enable[0]*(OPV_Weapon2_Probability-0.48252)	0.1618093	0.027541	5.88	<.0001*
OPV_Weapon1_Enable[0]*OPV_Forward Position[0]	-0.041445	0.00708	-5.85	<.0001*
OPV_Weapon1_Probability	0.1557493	0.026901	5.79	<.0001*
(Range to start counter measures-3150)*Helo_Active[0]	0.0000234	4.287e-6	5.46	<.0001*
OPV_Weapon2_ShotperSecond	0.0073734	0.001431	5.15	<.0001*

Figure 23. Sorted parameter estimates of the second order model.

Some terms of the second order model are polynomials and two-way interactions. For example, range to start counter measures is a quadratic term. That is, keeping all other factors constant, changing the value of this term changes the value of the mission success non-linearly.

When doing a regression analysis, it is also possible to fit the model with more degrees of interactions and polynomials. As a part of this regression analysis, three-way interactions were tested as well; however, they did not prove to be significant.

3. Partition Tree

An important technique for demonstrating the contribution of the factors to the response surface is building a partition tree. There are several other names given to this type of regression model, including Classification and Regression Tree (CART), and decision tree. The partition tree is mainly useful because it is easy to understand both for the analyst and the decision maker. It can demonstrate interactions, is relatively easy to build, and allows the analyst to easily explore the relationship between factors and the response. Furthermore, it can handle both numeric and categorical data (De'ath & Fabricius, 2000). Partition trees are often better at fitting jumps or plateaus in the data, and so they provide a convenient alternative to polynomial regression models when the response is not necessarily smooth.

A partition tree can be built using either the initial data with binary response or the aggregated data with continuous response. Both partition trees produce a similar tree structure. The contribution of the factors to the partition tree is similar as well. The partition trees used in this analysis were built on the raw data, which consists of 102400 data points and binary response.

When forming the partition tree, it is also possible to choose the set of factors on which the splits may occur. A full set of factors will provide insights on the relative importance of all the factors, whereas a small set of factors will help the analyst to see the effects of specific factors to the response surface. In the first part of partition tree analysis, all factors are included in the tree structure. In the second part, only the controllable factors are used to build the tree.

In the following parts of the partition tree analysis, the color blue represents the mission success of the friendly assets, and the color red represents the mission failure or enemy success.

a. Partition Tree to Include All Factors

In this part of the analysis, all the controllable and uncontrollable factors are included in the set of factors where the splits can occur. A portion of the partition tree for the mission success is shown in Figure 24. The probability of mission success or mission failure is demonstrated in the rectangles for each leaf of the tree. For example, the first split of the partition tree occurs with the factor "range to start counter measures." When the range to start counter measures is greater or equal to 1282 meters, the probability of mission success is 0.7749. When this range is lower than 1282 meters, the probability of mission success is 0.4745.

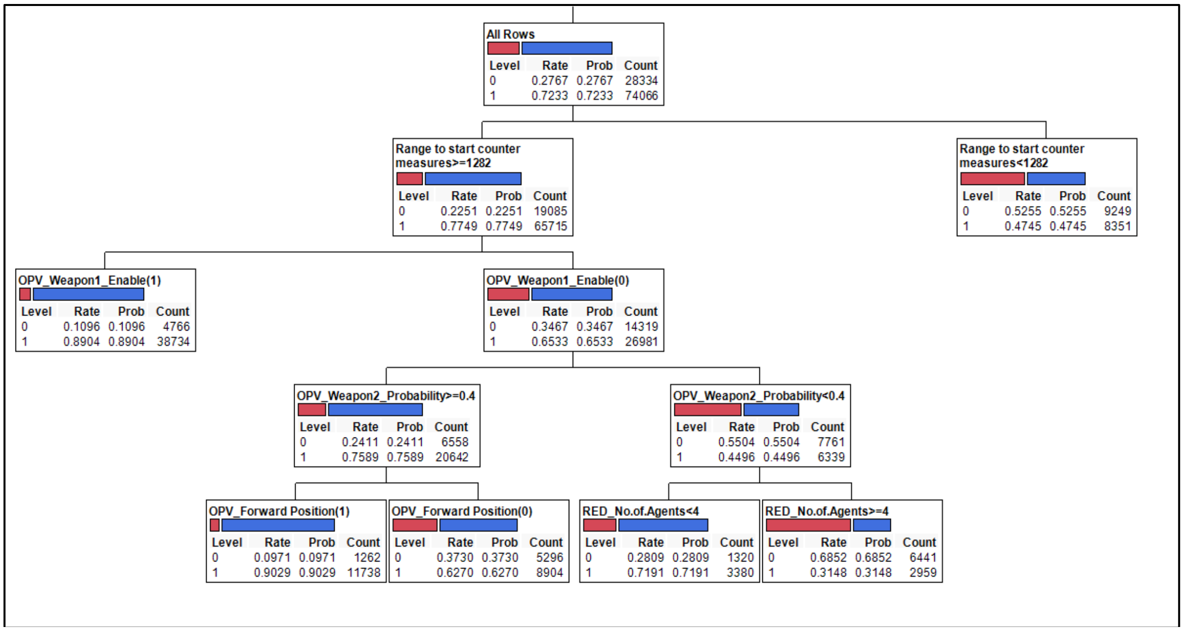


Figure 24. Portion of the partition tree to include all the variables. Blue represents the probability of mission success and red represents the probability of mission failure.

In this partition tree, the second and third splits occur on whether the main gun is available or not, and the probability of hit for the auxiliary gun, respectively. If the range to start counter measures is greater than or equal to 1282 meters, and if the main gun is enabled, then the friendly assets have almost a 90% chance of mission success.

The partition of the data can also be depicted with a partition graph as shown in Figure 25. In this graph, each hierarchical level from down to top represents the levels of the partition tree.

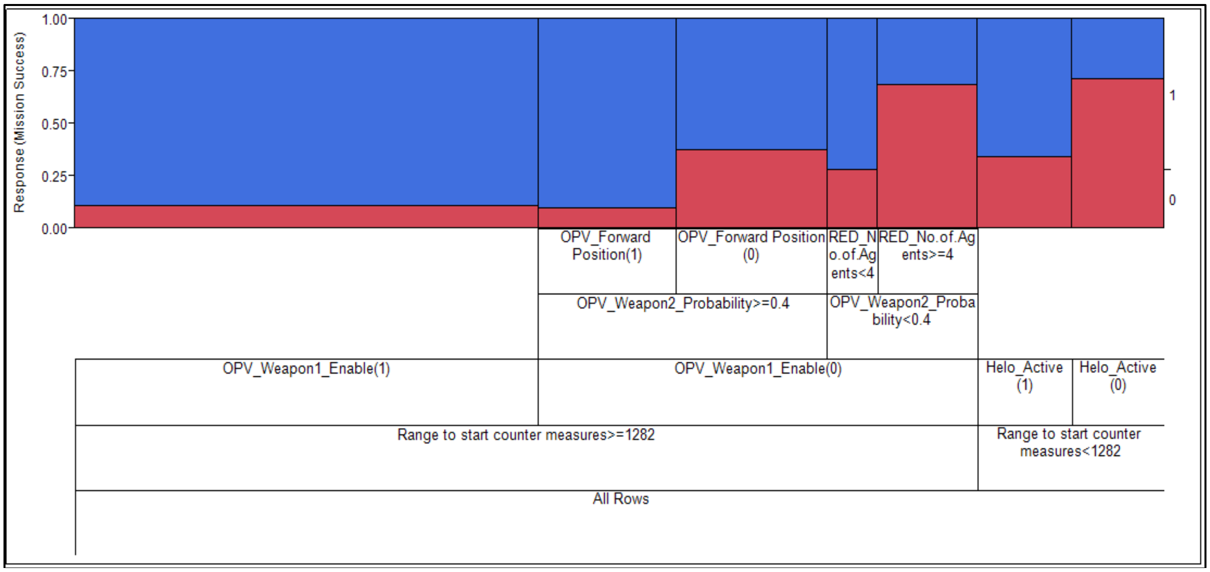


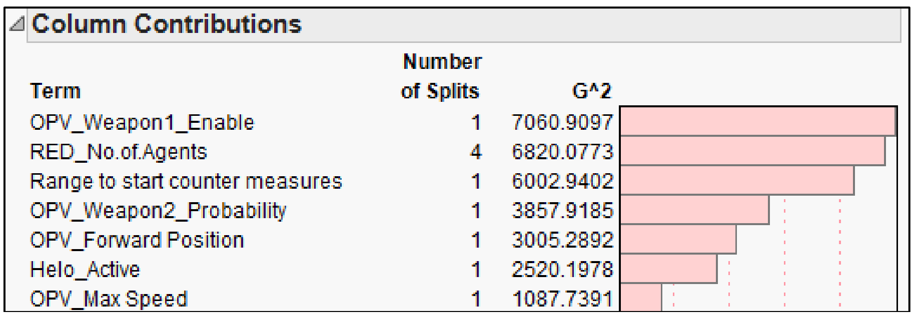
Figure 25. Partition graph for mission success to include all the factors. Blue represents the probability of mission success and red represents the probability of mission failure.

When the OPV starts firing early and uses the main gun, the probability of mission success is quite high. But what if the OTC does not want to use the main gun, or what if the main gun needs maintenance? In this case, the probability of hit for the auxiliary gun comes into play as an important factor. If the probability of hit of the auxiliary gun is greater than 0.4, and the OPV is in the forward position as a leading ship, then the friendly assets can still achieve high probability of mission success. On the other hand, if the hit probability of the auxiliary gun is lower than 0.4 and there are four or more hostile boats, the probability of success decreases to 0.25.

The ROE specify how close the hostile boats must be for the ship to start counter measures. If this distance is short, then having a helicopter becomes more important. The reason for that is the OPV does not leave the HVU alone to go ahead and classify the unknown targets. When there is no helicopter, the only way for classification is by visually analyzing the target and warning it. If the target does not seem to care about the warnings and continues its approach, then it is classified as enemy within a certain distance depending on the ROE.

When the helicopter is available and it detects an unknown target, it goes above the target to classify it. In this case, even when the target is farther away from the HVU, it can be classified as hostile or neutral; the friendly assets can start counter measures if it is classified as hostile.

When there are ten splits in the partition tree, the contribution of the factors to the mission success is shown in Figure 26. The factors that are significant are similar to the significant factors of the regression models as discussed in more detail later in this chapter.



Column Contributions

Term	Number of Splits	G^2
OPV_Weapon1_Enable	1	7060.9097
RED_No.of.Agents	4	6820.0773
Range to start counter measures	1	6002.9402
OPV_Weapon2_Probability	1	3857.9185
OPV_Forward Position	1	3005.2892
Helo_Active	1	2520.1978
OPV_Max Speed	1	1087.7391

Figure 26. Factor contributions for partition tree with 10 splits, both controllable and uncontrollable factors.

b. Partition Tree to Include Controllable Factors Only

In a naval mission, the decision maker has very little or no control of the factors related to the enemy or to the merchant traffic. Therefore, what the analyst should pay more attention to is the controllable factors. For instance, the decision maker may not be able to change the number of hostile boats, but he or she can change the number of machine guns on the OPV. The partition tree with only the controllable factors included in the model is demonstrated in Figure 27.

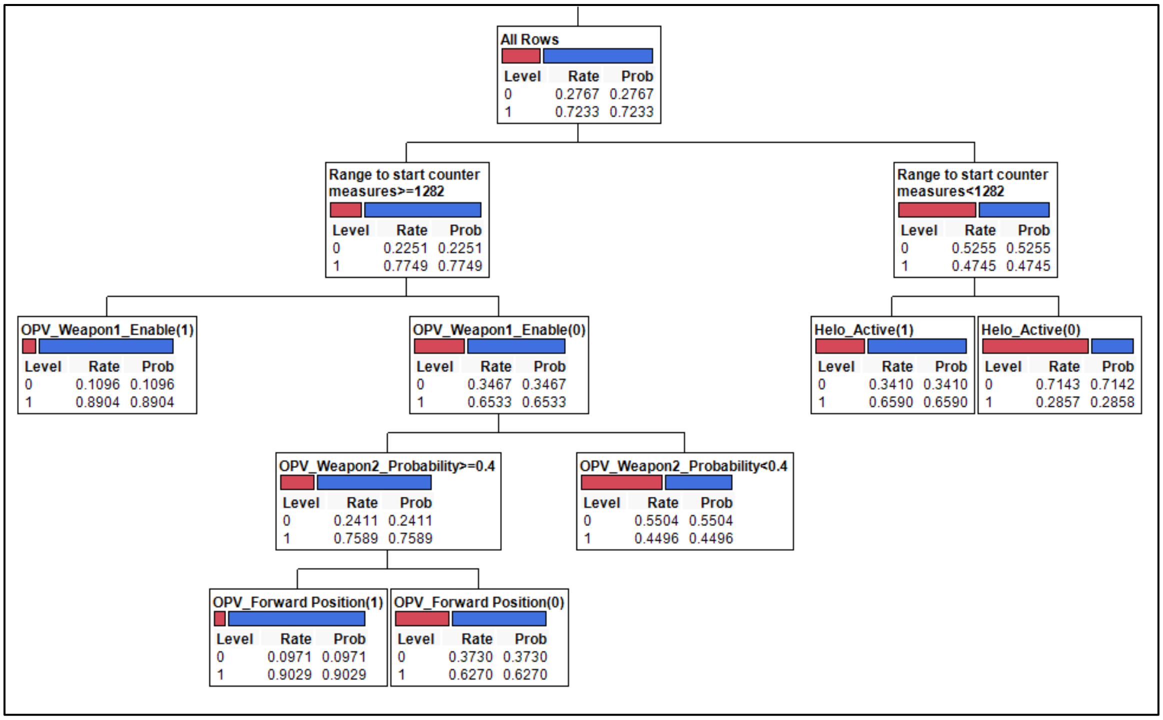


Figure 27. Portion of the partition tree to include controllable factors only. Blue represents the probability of mission success and red represents the probability of mission failure.

Since most of the significant factors are controllable, the structure of the tree does not change significantly. The number of the enemy boats does not show up in the tree since it is an uncontrollable factor. The partition graph shown in Figure 28 gives a more detailed split of the data.

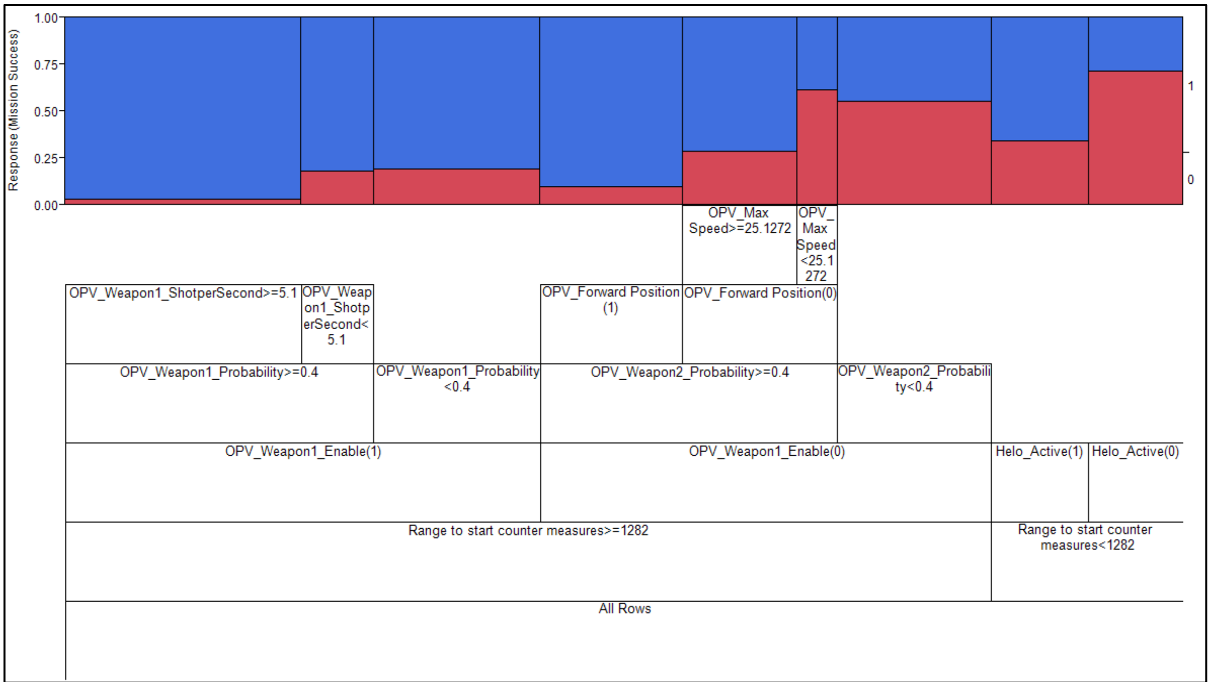


Figure 28. Partition for mission success to include controllable factors only. Blue represents the probability of mission success and red represents the probability of mission failure.

At the top level, the contribution of the OPV's speed to the mission success seems to be important in certain situations. It has been discussed that when the OPV starts counter measures from a long distance and cannot use the main gun, then the hit probability of the auxiliary gun becomes a significant factor. Yet, if the OPV is not the leading ship, there is still high risk in mission success when the OPV's maximum speed is lower than 25 knots.

An interesting split shown in Figure 28 is the effect of the main gun's hit probability to the mission success. Although having a higher probability of hit increases the chance of mission success, it does not improve the outcome substantially. More discussion of the hit probabilities appears later in this chapter.

E. FACTOR SIGNIFICANCE

The key drivers of the shipbuilding process are the operational effectiveness and the cost effectiveness. Decision makers of the naval acquisition and shipbuilding processes want to minimize the cost while, at the same time, maximize the operational effectiveness of the naval combatants. On the other hand, decision makers at sea, the naval officers, do not primarily care about the acquisition cost. Their purpose is accomplishing the mission. Factor significance is paramount for both groups for understanding the relative importance of factors in the shipbuilding process and in the operational environment.

For the ASUW scenario studied in this thesis, the comparison of the key factors (either controllable or uncontrollable) and their rankings in the meta-models are given in Table 8. The first six factors showed up in all of the regression models, and they proved to be significant with slightly different rankings.

Factors	**Logistic Regression Model**	**Main Effects Model**	**Second Order Model**	**Partition Tree**
Main Gun Presence	1	1	1	1
Number of Hostile Boats	2	2	2	2
Leading Ship Choice	3	3	3	5
Range to Start Counter Measures	4	4	5	3
Auxiliary Gun Hit Probability	5	5	4	4
Helicopter Presence	6	6	6	6
OPV Speed	11	11	-	7

Table 8. A comparison of the significant factors and their rankings in different regression models and partition trees.

The main gun is the most significant factor affecting the outcome of the mission. When the main gun is enabled, the result is generally in the friendly force's favor. On the other hand, if the main gun is not enabled, but the probability of hit for the auxiliary gun is high, the friendly assets can still achieve favorable results.

The second most important factor appears to be the number of hostile boats. It is obvious that when the number of enemies increases, the friendly force is less likely to win. This is an uncontrollable factor; although the decision makers should consider the number of the enemy in their plans, there is almost no way to control this in the operational environment. However, there are two alternatives. First, it is possible for the analyst to choose a more likely value as an input and to perform the analysis using the fixed value. For instance, if the expected number of terrorist boats is at most two, the data analysis can be performed taking two as constant when scoping the scenario. Second, if a robust alternative is found, that means that while the number of enemies has some effect on the overall mission success, the decision maker's plans do not depend on advance knowledge of the enemy strength.

Leading ship choice is another significant factor that showed up in all of the regression models. This factor is purely dependent on tactical decisions, and the author believes that this is something the decision makers will love to see. An important factor that is not directly related to the capabilities of the ship may eventually result in substantial reduction of the cost of the naval ships. If a warship can achieve the same goal with less capability, why not buy the cheaper ship instead of the expensive one?

Range to start counter measures is mainly related to the ROE, but also related to the tactics and the capabilities of the ships. Generally, if the ROE permits, starting to fire early increases the chance of mission success. If not, then other factors such as hit probability become more important.

A helicopter is one of the key assets of a warship; however, it is not as important in every operational scenario. If the ship is tasked in a search and rescue mission, then the helicopter will possibly be the most significant factor. In this scenario, on the other hand, it is not one of the top five significant factors.

OPV maximum speed does not appear to be a key factor in the ASUW scenario studied in this thesis. If the maximum speed of the OPV is not very high, this can be compensated with tactical decisions such as ordering the ship to be the leading ship.

F. DISCUSSION AND OPERATIONAL INSIGHTS

The technological advances in electronics led engineers to build powerful warships since the 1900s. Some people began to think that the more capable the ship, the greater the chance of mission success. Although this idea might be true in some cases, the capability of the ships might not be the key driver of mission success in every task.

There are important practical implications of the data analysis done in this thesis. The naval officers should be aware of the fact that tactical decisions may be a game changer in favor of the side which uses tactics appropriately. Several examples of practical implications and operational insights gained from this study are explained in the following paragraphs.

1. Weapons

Most of the surface combatants throughout the world have main guns. Nevertheless, it might be the case that OPV is not allowed to use the main gun due to the ROE, due to malfunction, or because there are merchant vessels nearby. In such situation, the OPV needs an auxiliary gun with high probability of hit. In many cases, however, increasing the probability of hit of the auxiliary gun may not be possible. The best way to overcome this problem appears to be well trained personnel. This will ensure that the hit probability of the machine guns will turn this disadvantage into an advantage. Thus, the commanding officer (CO) of a ship should pay more attention to the training of the machine gun operators, especially when deployed in areas with a high number of merchant vessels present.

Although the presence of the main gun appears to be one of the most influential factors, its probability of hit did not show up as important. This made the author question the model and the analysis. Further investigation of the data showed that there are sound reasons to explain why the main gun's hit probability did not show up as significant. A graph of main gun's hit probability versus the probability of mission success is shown in Figure 29. Note that this graph only shows the mission success in the cases where the main gun is enabled. The probability of mission success increases slightly with the probability of hit up until the probability is equal to 0.5. At first glance, probability of hit higher than 0.5 does not seem to make an additional impact on the outcome of the mission. One of the reasons might be that it may be more difficult to increase the chance of mission success when it approaches 100%.

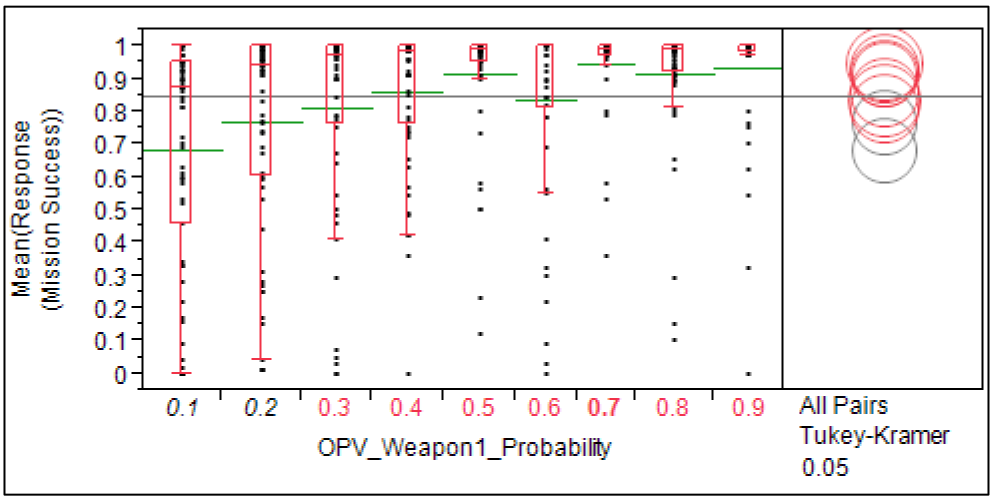
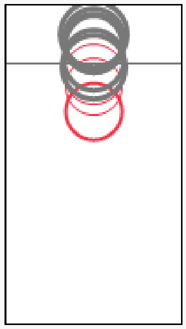


Figure 29. Main gun's hit probability vs. mission success probability.

A Tukey-Kramer test performed on the data proved that the probability of mission success is not statistically different when the hit probability is greater than or equal to 0.3 (Figure 30). The practical implication is this: having a main gun with probability of hit equal to 0.3 will give similar outcomes when compared to a main gun with probability of hit equal to 0.9. This information yields important insight: increasing a gun's probability of hit may not always increase the chance of mission success significantly. However, it decreases the variation and, therefore, decreases the risk of catastrophic failure. Greater probability of hit results in greater robustness.

Connecting Letters Report



Level				Mean
0.7	A			0.94851064
0.9	A			0.93456140
0.8	A			0.91781250
0.5	A			0.91661017
0.4	A	B		0.85948276
0.6	A	B		0.83360000
0.3	A	B	C	0.81175439
0.2		B	C	0.76830769
0.1			C	0.68365079

All Pairs
Tukey-Kramer

Figure 30. Connecting letters report for the Tukey-Kramer test. Levels not connected by same letter are significantly different.

Another insight gained from this analysis is that in the ship acquisition process, it may not be crucial to buy the “most advanced” technology. The naval combatant might be able to accomplish the mission with less capable and cheaper systems.

2. Helicopter

A challenging problem for the OTC or the CO is to decide when to start firing at the hostile targets. If the OPV is not allowed to fire from a long distance because of the ROE, or if the CO is willing to wait to be sure about the classification of the enemy, then the importance of having a helicopter in the mission becomes more obvious. The helicopter ensures that the friendly assets classify a ship as hostile from a longer distance. Once it is classified, then there is no problem firing at hostile boats at long distances from the HVU.

3. Range to Start Counter Measures

In “Data Analysis” it is mentioned that the range to start counter measures is a quadratic term of the second order model. What does it mean in terms of naval operations? A snapshot of the prediction profiler for this factor is shown in Figure 31. Initially, the probability of mission success increases rapidly with the range; however, when the range approaches to 3000s, increasing the range does not affect the mission success as much. Furthermore, since the friendly force does not have an unlimited number of rounds and since the weapons can malfunction with intense use, starting to fire too early may result in a decrease in the probability of mission success.

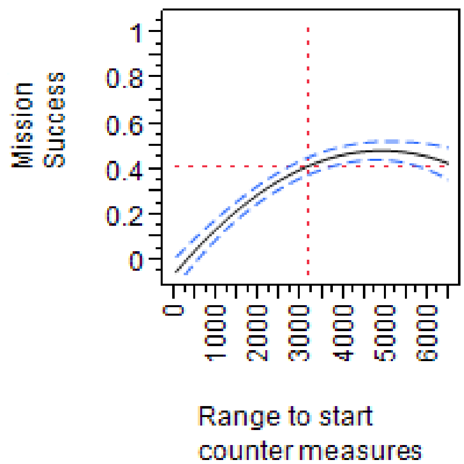


Figure 31. Prediction profiler for range to start counter measures.

This shows that analytical tools should be used to enhance our knowledge about even obvious tactical decisions and ROE. Moreover, the author believes that many of ROE may be tested in the simulation environments, and reconsidered in the light of technological advances and experience periodically.

4. Leading Ship Choice

The analysis in this thesis showed how a tactical decision might impact the outcome of a mission. Leading ship choice is a tactics related factor, and it helps the naval officer to better understand the nature of the naval warfare.

When the convoy is navigating eastward as in this scenario and the OPV is the leading ship, one of these three events might happen:

- The hostile boats may approach from the east as shown in Figure 32. In this case, the OPV can quickly impede them since it is between the HVU and the hostile boats.

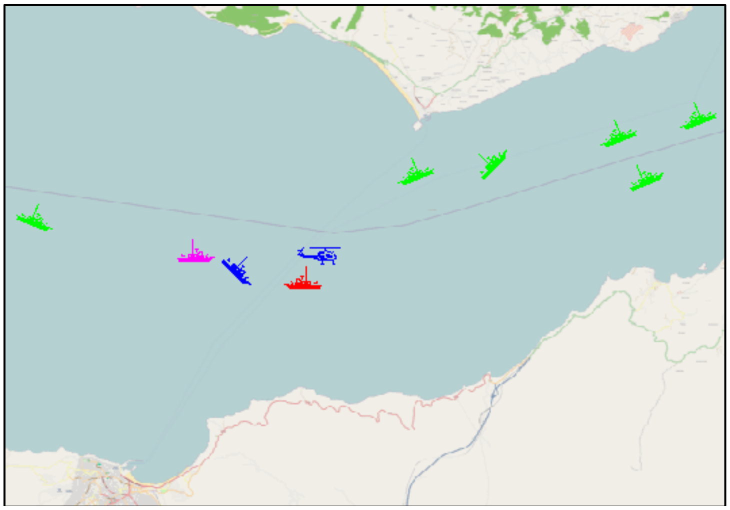


Figure 32. Hostile boat approaches from east.

- The hostile boat may approach from the west as depicted in Figure 33. In this case, since the relative speed between the convoy and the hostile boat is smaller, it takes much more time for the hostile boats to reach the convoy. When the OPV changes its course to the west and navigates towards the hostile boat, it increases the relative speed between the hostile boat and itself, and again quickly impedes the hostile boat while the HVU continues on its course.

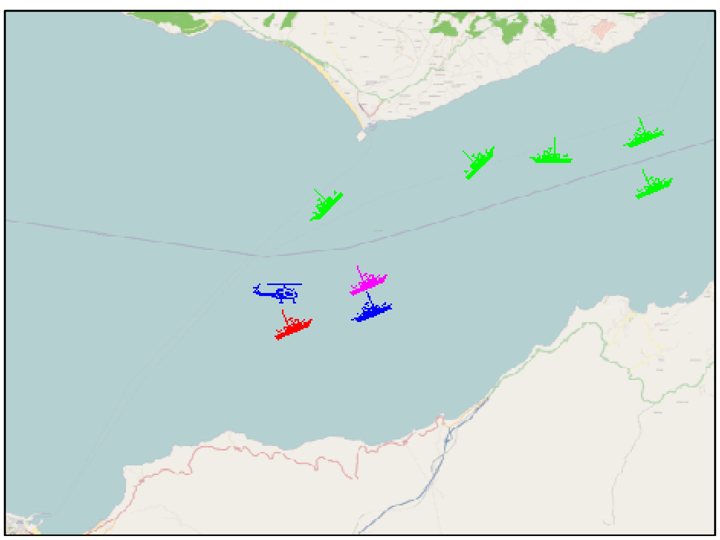


Figure 33. Hostile boat approaches from the west.

- The hostile boats may approach from north or south. In this case it will not be very important whether the OPV is the leading ship.

5. Interaction of the Factors

Interaction of the terms in a model is also important both for the analyst and the decision maker. The interaction plot for the second order model is shown in Figure 34.

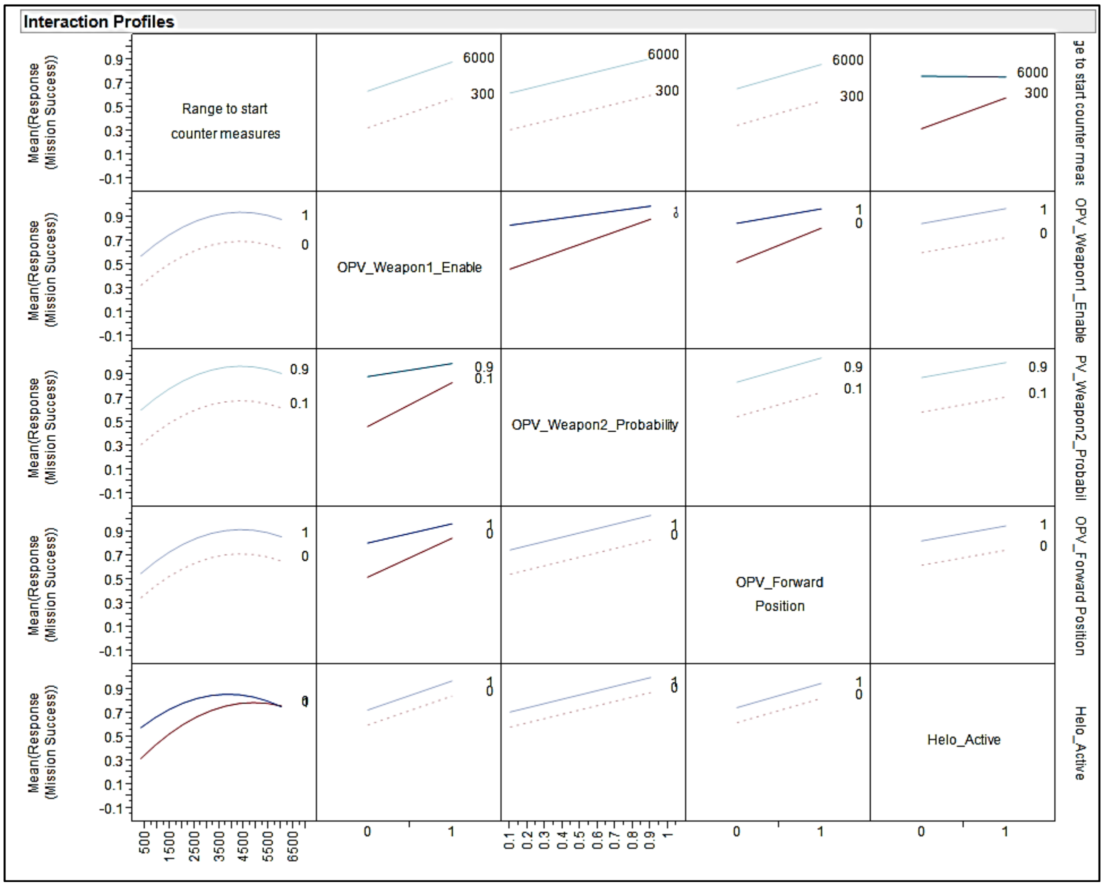


Figure 34. Interaction plot for the second order model.

The interaction between range to start counter measures and the presence of the helicopter seem to be the most significant. If the range to start counter measure is high, the helicopter’s presence has less effect on the mission success. If the OPV cannot start firing early, then the helicopter becomes more important. Therefore, in the areas where there is significant maritime traffic, the OTC or CO should consider using the helicopter.

The presence of the main gun appears in interactions with both the auxiliary gun’s hit probability and the leading ship choice. When the main gun is enabled, the hit probability of the auxiliary gun becomes less important. Similarly, when the leading ship is the OPV, whether or not the main gun is enabled has less effect on the outcome.

The main insight gained from interactions is that theydemonstrate a simple way to perform trade space analysis between the choices. For instance, if the main gun is malfunctioning, the decision maker should consider putting the OPV in the front and making the other guns more effective.

6. Insignificant Factors

Last, but not least, having a significant factor which appears in each model is important; however, it is almost equally important not seeing a factor in the significant factors list. That means the decision maker can be more flexible in his or her decisions for that specific capability or tactic.

Moreover, if a factor is not important in the presence of others, this does not mean that it is not important by itself. For instance, the probability of hit for the main gun did not show up as a significant factor. However, if the auxiliary gun is somehow in non-working condition, the hit probability of the main gun becomes more important. A trade space analysis is therefore crucial in the early stages of the acquisition process.

G. OTHER IMPLEMENTATIONS OF THE COMBAT MODEL

The scenario built for this thesis was also used in two other ways. First, it was used to test the new version of MANA. An experiment on both versions showed that the results were not significantly different than the results of the previous version of MANA.

Following this experiment, more factors were added to the design such that the number of factors to be tested was increased from 35 to 65. These factors were changed by very small amounts, and so were not expected to have important impacts on the mission success. Rather than running a new 512-design-point experiment, a new Lasso-optimal screening design was replicated 1000 times, and the resulting data were analyzed. The supersaturated screening design used in this method uses only two levels for each factor and can examine up to 69 factors with only 24 design points. The results revealed that some of the design points cause the simulation to crash. Building the partition tree shown in Figure 35 demonstrated that in some cases MANA could not complete the simulation for this specific scenario. The problem only occurs when Squad3 (the helicopter) is active, and when a specific personality value of this agent is non-zero. These surprising results show how a well-designed screening experiment can be a useful and efficient approach to model verification: it would have been much more difficult to identify the software problem using a trial-and-error approach.

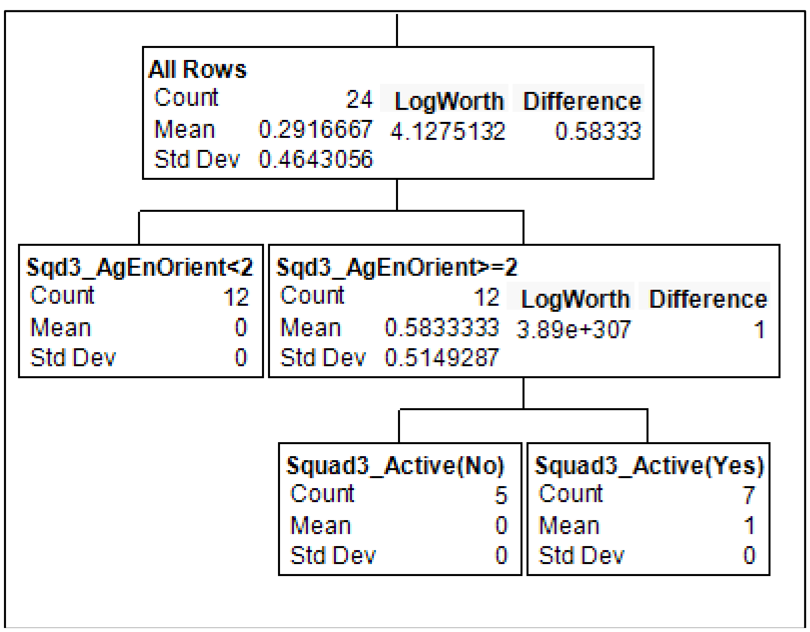


Figure 35. Partition tree to show the factor which causes MANA to crash.

Finally, the problematic factor was removed from the study and replaced with another in order to test the analysis capabilities of a newly proposed Lasso-optimal analysis method for this screening design (Xing, Wan, Zhu, Sanchez, & Kaymal, 2013). The purpose of this effort is to identify significant factors in a simulation. Lasso is a popular tool in data mining. It is mainly useful when the number of factors is large, and only a small subset of those factors is important. Therefore, it has been proposed that Lasso can be used to design and analyze screening experiments, even though it is known to give biased estimates. The results were mixed for this ASUW scenario: the Lasso model included several factors that were not identified in the larger design and omitted several that were. Further research is underway to see whether the existence of important interactions confuses model identification for Lasso, or whether some of the additional factors are truly important.

V. CONCLUSION

A. OVERVIEW

This research investigated the impacts of capability and operational related decisions to mission success of surface combatants in an ASUW environment. A scenario was built based on a real world incident, and it was implemented in the combat modeling platform MANA. 102400 simulations were performed in total, and the output of the simulations was analyzed using a variety of statistical methods. The results of the analysis yielded important insights for the decision makers. Both the tactical decisions and OPV capabilities were proved to be important for mission success.

B. RECOMMENDATIONS

The ASUW scenario analyzed in this study provides valuable insights regarding the naval shipbuilding process, employing tactics, and ROE. The following recommendations are based on the insights gained from the results of the analysis:

- The acquisition of the naval ships needs thorough analysis regarding capability, cost, and operational effectiveness.
- The decision makers of the shipbuilding process, and the decision makers at sea (i.e., the naval officers) should work together to set the requirements for a ship design.
- Trade-space analysis is a valuable tool to understand the impact of the various factors.
- Many factors affect the result of a naval mission. Among these, there is not "one" set of decisions that provides the mission success. There are numerous ways to achieve the same result.
- Bigger scale modeling and simulations can be performed to analyze the operational effectiveness of the naval ships in various

tasks. This will help the planning of the CONOPS along with the shipbuilding process.

These recommendations represent the general idea of the implications of this research. There are many more insights that can be gained by the reader.

C. FURTHER RESEARCH

This research analyzed only one ASUW scenario that a naval ship may face. Building other scenarios for ASUW and for other warfare areas may improve the NPS Dashboard. This fine-tuning will help the decision makers better understand the trade-space between factors affecting a naval mission. Another important study that can be done is building a combat model that incorporates several warfare areas such as ASUW, ASW, and AAW at the same time.

For the researcher who wants to expand the scenario studied in this thesis, the following improvements can be added to the combat model in order to make a more thorough analysis:

- Setting aperture angles for the weapons and sensors
- Increasing the number of OPVs
- Using several UAVs instead of a helicopter
- Allowing terrorists to carry weapons such as rockets.

D. SUMMARY

In the past, the experience of the sailors was the main driver of the tactical decisions. Today, it is the technology and the science that shape tactical decision making more intensely. Naval officers should know the characteristics of their ships, and they should rely not only their experience but also on analytical tools to form their decisions. Choosing the right course of action may reduce the emphasis on capability as the primary factor in decision making. This change has the potential to reduce the acquisition cost of a naval ship while improving the navy’s prospects for achieving mission success.

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